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PULSE WIDTH MODULATOR CONTROLLER DESIGN FOR A BRUSHLESS DC MOTOR POSITION SERVO

by

Vincent S. Rossitto

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Thesis Advisor: Alex Gerba, Jr.

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a preliminary parametric design of the controller. Comprehensive electrical and mechanical analyses were conducted using detailed model simulation to arrive at the final design by parametric optimization. FORTRAN source code listings for all simulations discussed in this thesis are appended and were run on a personal computer.

Pulse Width Modulator Controller Design for a Brushless DC Motor Position Servo

by

Vincent S. Rossitto
Lieutenant, United States Navy
B.S., United States Naval Academy, 1978

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ABSTRACT

Recent interest in positioning cruise missile flight control surfaces using electromechanical actuation has prompted a detailed study of brushless dc motor performance in such an application. While the superior response characteristics of these electronically commutated motors are particularly well suited to unidirectional velocity drives, destructive electrical transients associated with rotational reversals of the motor limit its positioning performance. This thesis involves computer aided design of a functionally robust brushless dc motor position controller using pulse width modulation. Lumped parameter model simulation and phase plane analysis were performed to attain a preliminary parametric design of the controller. Comprehensive electrical and mechanical analyses were conducted using detailed model simulation to arrive at the final design by parametric optimization. FORTRAN source code listings for all simulations discussed in this thesis are appended and were run on a personal computer.

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I. INTRODUCTION

A. BACKGROUND

The ever increasing demand for small, high performance motors for use in such applications as missile flight and space vehicle control actuators, robotics, and disk drives, justify development of brushless dc motor technology.

Although conventional dc motors are highly efficient and are proven to be well suited for servo motor application, brushless dc motors are generally superior in performance. Perhaps the most significant factor in the recognition of the permanent magnet dc motor as a viable electro-mechanical actuator is the recent advances made in the area of rare-earth magnetic materials. Despite the increased initial cost of samarium-cobalt, for example, its characteristically high magnetic remanence and coercive force provide about twice the flux density of a similar ferrite magnet. The increased torque-to-inertia ratio is desired in high performance actuators. Additionally, improvements in semiconductor technology have further enhanced the realization of electronic commutation. Rapid switching characteristics and low power consumption of solid state devices have widened the gap in performance between brushless and conventional dc motors. Field windings of a brushless dc motor are located in the stator with permanent magnet in the rotor and commutation is performed using solid state devices, resulting in cooler motor operations. Inherent to the removal of mechanical brushes and commutators is the elimination of arcing and general maintenance associated with conventional dc motors. The physical separation of commutation electronics and the motor provide for a much smaller actuator, capable of functioning in areas previously thought to be too restrictive for electro-mechanical actuation.

B. PURPOSE

Although application of brushless dc motors is rapidly expanding, their popular use is inhibited by the requirement for relatively complex control and power conditioning electronic circuitry. The intrinsic high performance characteristics of these electronically commutated motors are particularly well suited to velocity devices, where the direction of rotation is not routinely reversed. Thus, recent exploitation has been primarily confined to variable speed drives. The intent of this study, however, is to design a functionally robust positioning device capable of cruise missile fin actuation over a broad range of missile flight dynamics.

Unlike the unidirectional kinematics associated with velocity controlled motors, positioning response is invariably characterized by rotational reversals. While the superior torquing capability of brushless dc motors supports high performance position control, the electronic components which facilitate commutation are subjected to excessive voltage transients and, hence, reduced operational reliability. The central theme of this study involves the design compromises required between system performance and corresponding electrical characteristics.

C. APPROACH

Graphic techniques employed in this thesis are supported by a variety of interactive computer aided design developed specifically for studying the behavior of brushless dc motors. Previous efforts by Thomas [Ref.1] and MacMillan [Ref.2] using the IBM 370 mainframe compiler serve as a foundation from which this study stems. All simulation is performed on a microcomputer rather than the IBM 370 mainframe, and lower level programming in FORTRAN77 replaces the Continuous System Modeling Program (CSMP) language [Ref.3]. While CSMP provides an excellent environment for general simulation, it impedes programming accessibility to various structural mechanisms and primarily provides output characteristics of imbedded functions. Along with enhancing process visibility, coding in FORTRAN facilitates program portability. An objective of this thesis is delivery of appropriate design tools to support on-going efforts in brushless dc motor development at Naval Weapons Center (NWC), China Lake.

Correlation between electrical and mechanical response characteristics of brushless dc motors is prerequisite to the design problem and best determined with the motor configured as an open loop velocity device. Power conditioner modifications which reduce high voltage transients are investigated. Pulse width modulation is examined as a method for providing accurate position control in a manner congruous with power conditioner electronic limitations.

Optimal selection of design parameters cannot readily be made with the detailed model of MacMillan due to the degree of its complexity. Therefore, preliminary design is accomplished using lumped parameter modeling which provides simulation simplicity, speed, and insight. Additionally, with limited availability of manufacturer's and experimental performance data, which is summarized in [Refs.4&5], the simplified model provides an excellent means of validation and verification of the brushless dc motor simulation.

Phase plane methods used in this study support the graphic nature of nonlinear design and provide considerable insight not only to system performance, but also to the motor's dynamics. The culmination of this study involves analysis of the linearly approximated design with the brushless dc motor computer simulation.

II. MODEL DESCRIPTION

A. BACKGROUND

Previous efforts in brushless dc motor simulation at NPS have exploited the IBM 370 mainframe and Continuous System Modeling Program (CSMP). Significant attractions of these assets include programming simplicity and computational versatility due mostly to stiff integration methods available. However, current microprocessor capabilities justify the development of such a simulation for analysis on a personal computer.

The programming language chosen for this undertaking is Microsoft FORTRAN77 V3.31. Graphic output is attained via subroutine calls to Plotworks PLOT88 graphics library. Because of the intense computational demand of the simulation, an INTEL 8087 numeric co-processor was exploited.

The motivation for conducting such a study on a personal computer lies in the inherent portability of the product. On-going efforts at NWC, China Lake in brushless dc motor design and analysis are not fully benefited by present NPS computer simulations because of mainframe inaccessibility. Additionally, batch processing of CSMP simulation results in cumbersome development of the model. While microprocessor architecture lacks the computational power of the mainframe, it is superior in terms of portability and work station availability. All simulations conducted in this study were performed on INTEL 8088/8086 machines, although the universal nature of FORTRAN coding could be easily implemented on any machine capable of being programmed in FORTRAN. The source code for the detailed brushless dc motor simulation program is listed in Appendix A.

The basic modeling structure delineated in MacMillan's work [Ref.2] is illustrated in Figure 2.1 and serves as the starting point of this study. Based on the assumption that the network is balanced and the power supply configuration is split, the relatively complex 3-phase bridge circuit shown in Figure 2.2 simplifies into the two window network of Figure 2.3 [Ref.4]. Back emf voltage of each phase is modeled by MacMillan and summed two at a time to determine loop currents. Reference 2 gives a detailed development of the power conditioner model which includes assumptions for the switching transistor dynamics used in commutation as well as the development of the harmonic air-gap flux used in the motor model.

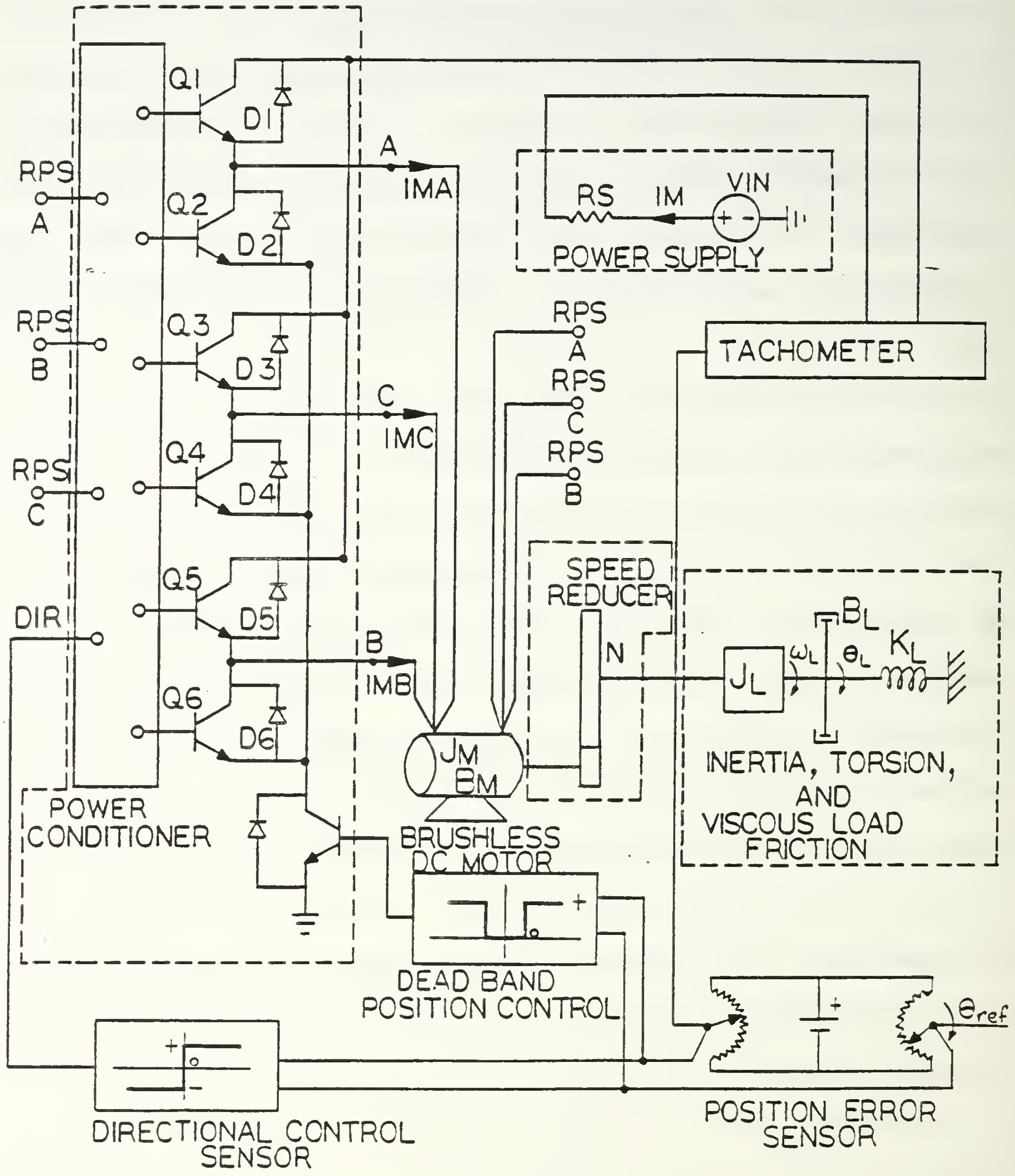


Figure 2.1 Basic Modeling Structure

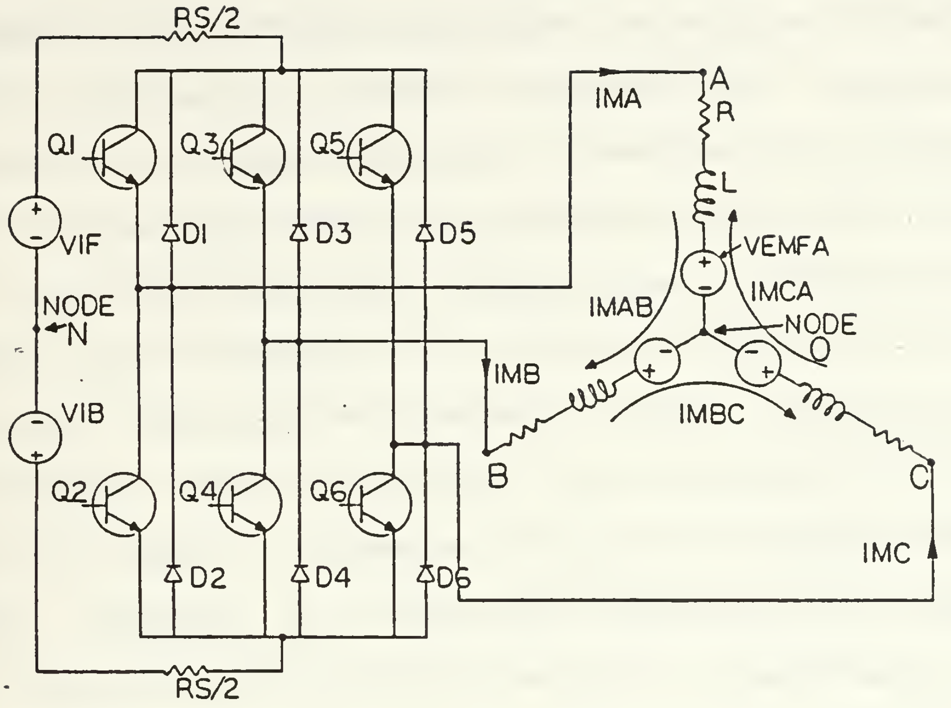


Figure 2.2 Three Phase Bridge Circuit

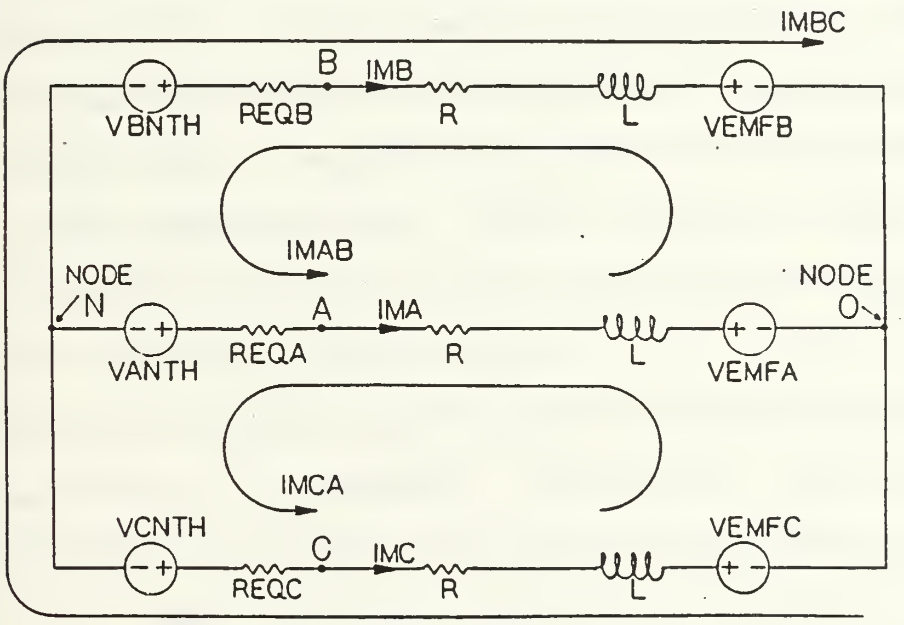


Figure 2.3 Two Window Equivalent Circuit

B. SIMULATION METHOD

Since the simulation environment intrinsic to CSMP is not available in FORTRAN, a viable means of dynamic programming was devised. Natural parallel processing observed in the behavior of electronic components of the motor is simulated using iterative numerical techniques.

Continuous system modeling is attained via the dynamic solution of two nested systems of coupled, nonlinear differential equations. The inner loop establishes incremental states of motor current. Using Thevenin equivalence techniques, potential is applied across nonlinear resistance. This resistance is dependent upon the state of diodes and transistors, as well as the linear resistance of the phase windings. An adaptive Newton-like method for solving these equations was developed. Of particular interest in the inner loop is the presence of multiple solutions, where lax iterative methods could result in convergence to an incorrect solution. Specifically, the parallel relationship between the nonlinear equivalent resistance and motor phase current allow for convergence to either the low or high diode resistance solution. This is particularly prevalent during periods of diode free-wheeling associated with commutation switching. The numerical solution of the inner system of coupled equations becomes extremely stiff and voltage sensitive near the bias threshold of the protective diode. A quantized two-state solution exists over a narrow range of inputs, resulting in somewhat unpredictable numerical convergence and possible local instability. One solution for phase current incorporates a relatively fast time constant due to the high equivalent resistance contributed by the non-conducting diode, while the conducting diode solution is described by a slower time constant.

The stiff characteristics of the inner loop are adequately handled through the use of a cautious iterative method which is invoked prior to numerical bracketing of the actual solution. During non-bracketed iterations, the simulation step is halved and the system's condition is investigated to ensure that the solution has not been bypassed. This halving technique increases the resolution of the high/low resistance solutions which might otherwise mask each other. This method works reasonably well, but numerical "chattering" is still observed during conditions immediately prior to diode turn-off. Although available stiff integration methods would further minimize the numerical oscillation, size and speed constraints prohibit such integration in this program.

The outer loop solves the motor's position and velocity states and the induced back emf characteristics simultaneously. A simple Newton iterative scheme works well on the outer loop because of filtering and smoothing provided by the motor's low pass response characteristics.

Despite numerically stiff behavior, the highly nonlinear and discontinuous nature of the model supports the use of a simple small step trapezoidal integrator. Variable step integration involves considerable coding structure and computation time during stiff conditions, neither of which is well suited for the limited architecture of a personal computer. Direct comparison of fixed step results gained in this simulation with variable step results described by MacMillan support the validity of fixed step integration. Convergence criteria establish the solution accuracy and efficiency and are monitored during the execution of the simulation program. Stiff numerical conditions which burden fixed step integration are identified and displayed at the console.

The successful modeling of an analog system in a digital simulation relies heavily on the step size. Particularly, the discontinuous nature of this model increases the likelihood of false response characteristics if the simulation interval is not carefully selected. Oscillations due to subharmonic interaction between the simulation increment and the discontinuous pulse width modulated forcing function may result. Position control with pulse width modulation is best simulated using a small, fixed step rather than a variable step scheme common to stiff integrators. As a general rule of thumb, the simulation step increment should be at least an order of magnitude less than the PWM reference period to eliminate aliasing and other problems associated with periodically sampled systems.

C. POWER CONDITIONER SIMULATION

Accurate modeling of power conditioning and commutation in brushless dc motors requires explicit definition of the physical behavior of power transistors and their associated protective diodes. Lower level programming is required to properly imbed the conditions necessary to naturally trigger the diodes and permit realistic simulation of their performance. It is presumptuous to force the diodes into the conducting state during the entirety of their thirty mechanical degrees of protective duty. Simulation of the natural behavior of electronic components is of particular importance when the model is configured for position control. Reversal of the direction of rotation may be ordered by the controller at any time or position. The randomness of the forcing function as observed by the power conditioning components necessitates that behavior algorithms be generalized to ensure simulation robustness.

Coil inductance action in brushless dc motors is significant and deserves particular attention in this study. When current, I, flows into a circuit whose inductance is L, the electromagnetic energy, E, will be stored in it and is given by Equation 2.1.

$$E=\tfrac{1}{2}LI^2 \qquad (2.1)$$

The corresponding voltage across the inductive coil is determined by the change in current flow through it and is described by Equation 2.2.

$$V = L\,\frac{di}{dt} \qquad (2.2)$$

When the inductive circuit is opened, the voltage induced is generally sufficient to forward bias the appropriate free-wheeling diode and cause it to conduct. As long as a low resistance return path for the exponentially decaying current flow is provided, the corresponding voltage response is acceptable. If the protective diode changes to a non-conducting state because of component failure or reverse bias conditions, the equivalent resistance of the return path for current flow becomes very high. The resulting faster time constant of the circuit promotes rapid dissipation of any electromagnetic energy stored in the inductive coil. If significant energy remains stored in the coil at the time of diode turn off, a large di/dt and undesired high voltage condition will result.

Figures 2.4 through 2.9 describe step velocity current and voltage response characteristics for conditions where the protective diodes are both functional and inhibited. The key observations made from these six plots involve current decay rate dependence on the functional status of the protective diodes and the corresponding voltage conditions observed at the power transistors. Unacceptably high voltage transients that occur across the transistor/diode pair, as shown in Figure 2.8, result when free-wheeling diodes malfunction. Voltage spikes are limited to 800 volts in the computer simulation for purposes of graphic scaling. In Figure 2.9, functioning diodes are observed to reduce peak voltage values to 240 volts. However, when current is decayed with a time constant smaller than the simulation step size, discontinuous behavior results. As long as current decay is numerically discontinuous, the induced coil potential determined by Equation 2.2 is principally dependent on the simulation step size. Therefore, the magnitude of the voltage spike resulting from the rapid decay of 12 amps of phase current is dominated by coil potential and may be approximated analytically.

$$V = L_{eq} \frac{di}{dt} \simeq 2L_{eq} \frac{\Delta I}{\Delta T}$$

$$\Delta I = 12 \text{ amps} \ ; \ \Delta T = 4\tau_{decay} = 4L_{eq}/R_{eq} \simeq 0.64 \ \mu\text{volts}$$

$$V \simeq 30{,}000 \text{ volts}$$

For di to be approximated as ΔI at a value of 12 amps, then Δt may be chosen as small as four times the high resistance decay time constant, τ_{decay}. Clearly, 30,000 volts of potential across a power transistor is not realizable and junction punch through would most likely relax this condition. However, resulting transistor damage is highly probable. The acceptable peak voltage conditions depicted in Figure 2.9 are affected, but not dominated, by induced coil potential. As shown in Figures 2.5 and 2.7, motor and phase current is decayed with the low resistance time constant, allowing reasonable dissipation of stored electromagnetic energy from the coil.

Digital simulation of an analog component or circuit generally may be accomplished using numerical methods and a step size sufficiently small to preserve the formation of its continuous response characteristics. However, the parallel processing behavior of the inductive coil in a highly nonlinear and discontinuous environment is not modeled as easily.

A protective diode is triggered when its biasing threshold is exceeded, usually the result of commutation switching action. Each finite increment of the digital simulation is uniquely described by a set of state conditions. The modeling of ideal diode characteristics introduces discontinuous behavior in the circuit and precludes numerical solution using simple iterative methods.

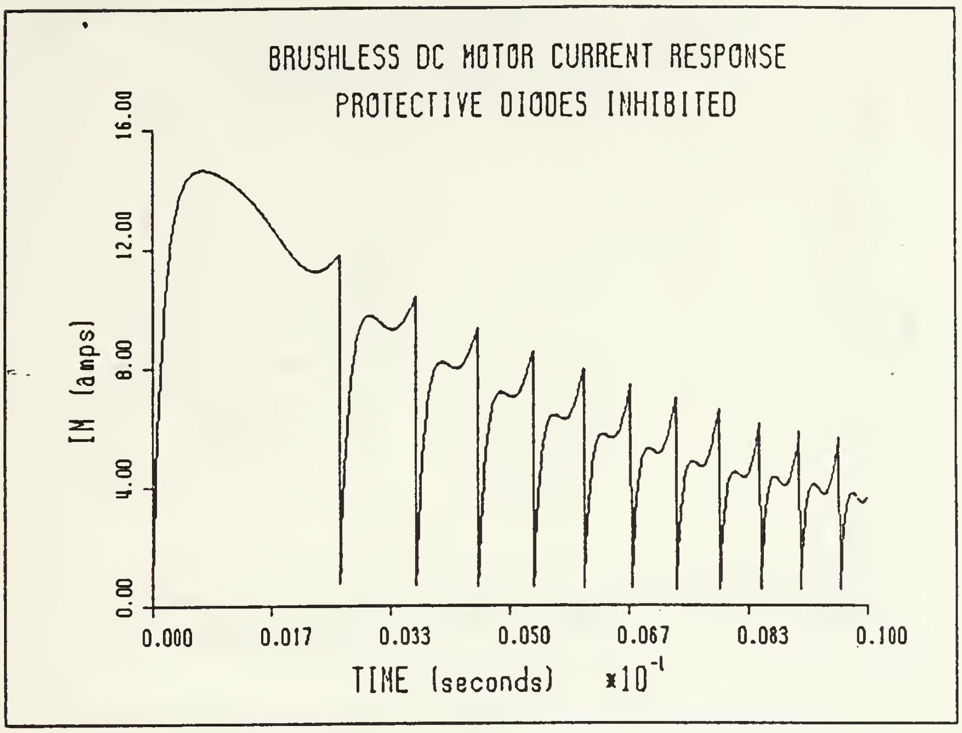


Figure 2.4 Motor Current Response with Diodes Inhibited

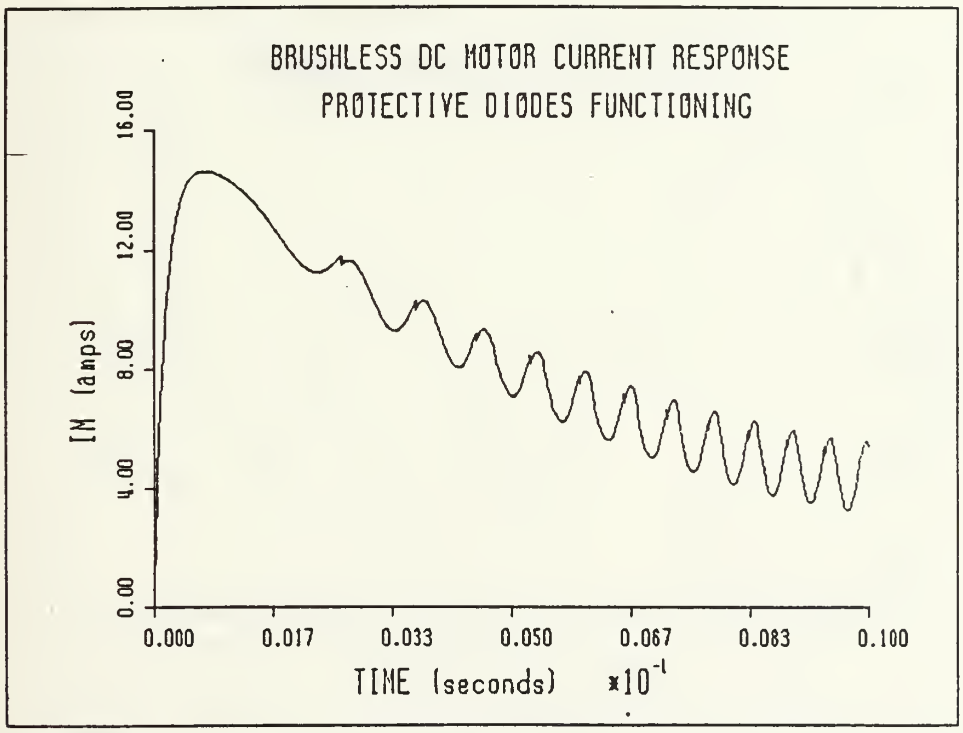


Figure 2.5 Motor Current Response with Diodes Functioning

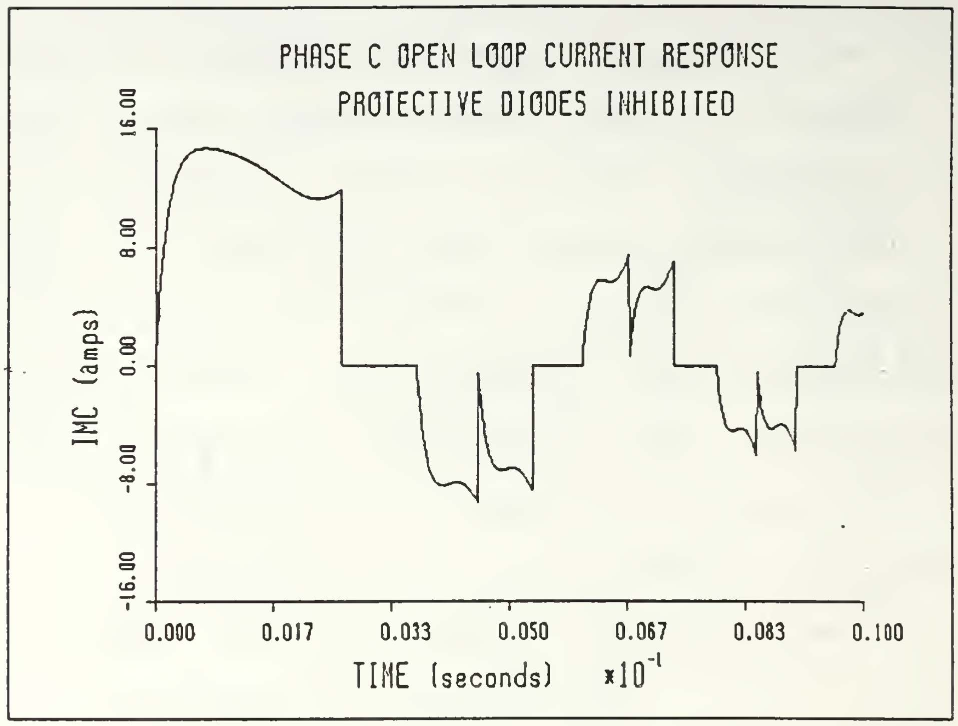


Figure 2.6 Phase Current Response with Diodes Inhibited

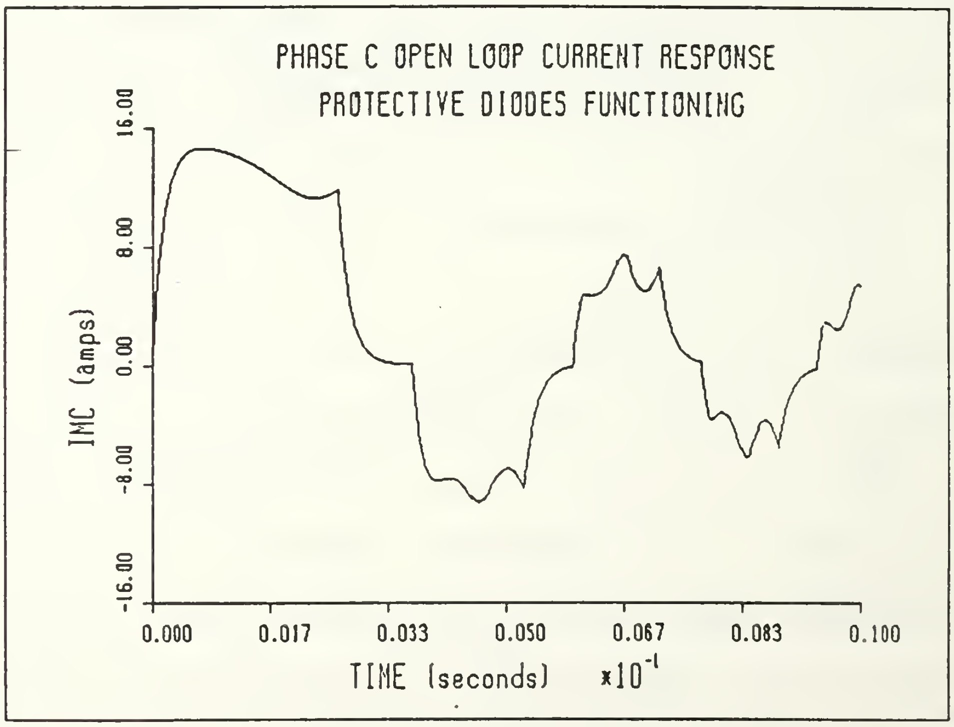


Figure 2.7 Phase Current Response with Diodes Functioning

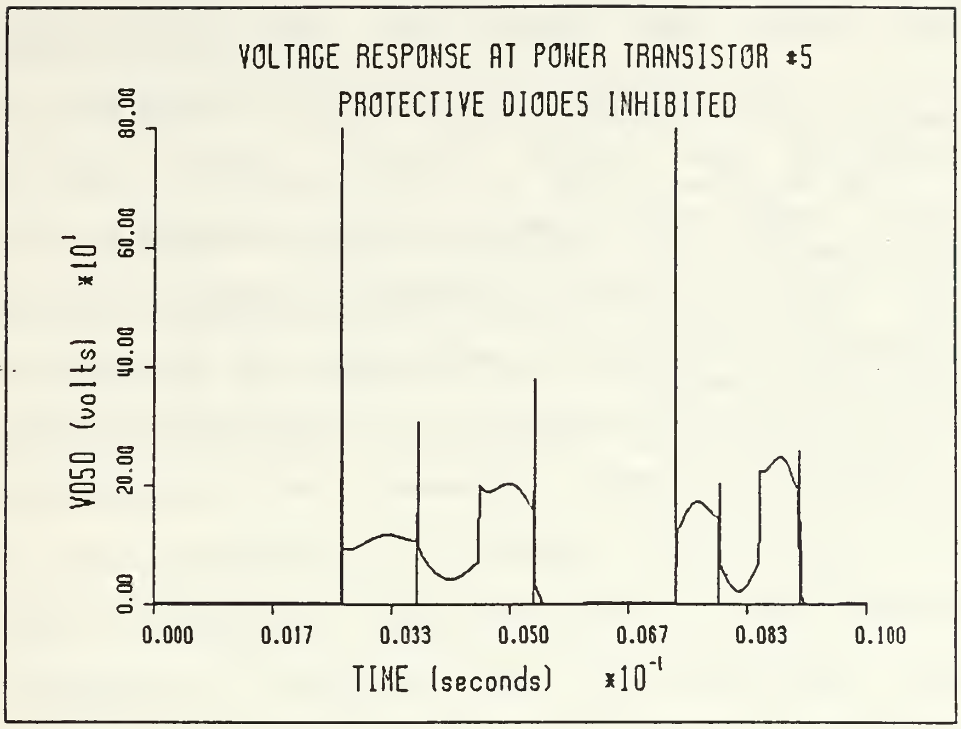


Figure 2.8 Voltage Response (Q5) with Diodes Inhibited

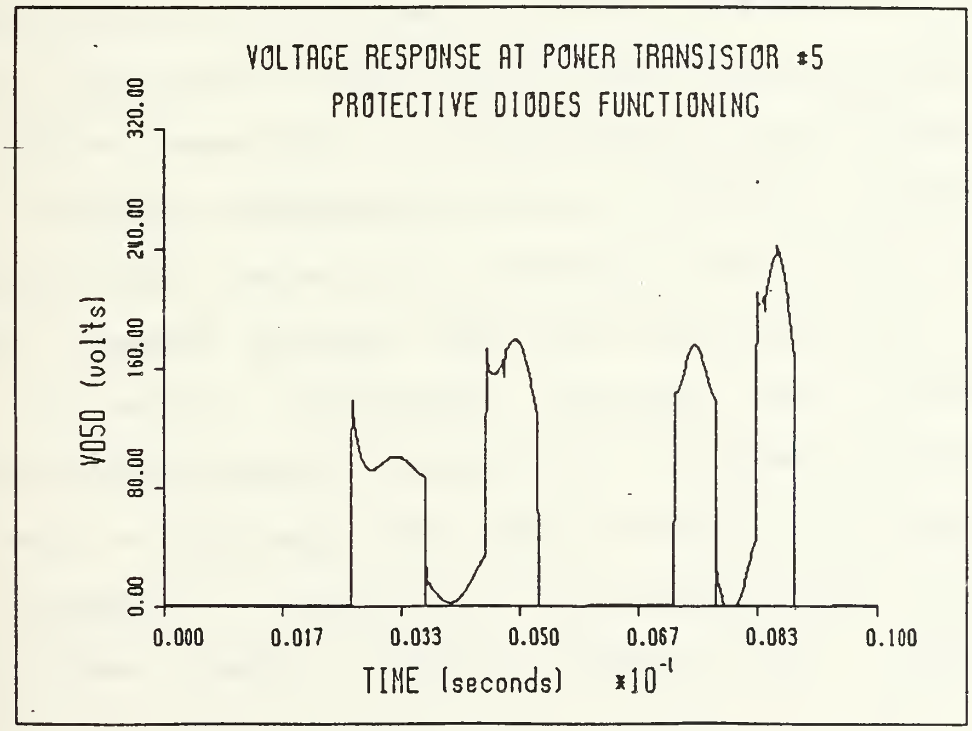


Figure 2.9 Voltage Response (Q5) with Diodes Functioning

Consider the incremental voltage and current response of an affected phase leg immediately following commutation switching. The voltage response of the inductive coil is determined by the current flow to which the coil is subjected. When the current flow is apparently cutoff, a large and negative induced voltage is immediately observed. This voltage condition is sufficient to forward bias the protective diode and provide a low resistance return path for the decaying current. However, the low resistance and positive current flow result in a voltage which reverse biases the diode. This apparent toggling of the diode presents difficulty in the numerical convergence and instantaneous solution for each affected step in the simulation.

If the step size could be reduced to an infinitesmally small period, analog simulation would be realized and the diode would behave realistically. Continuous modeling is alternatively achieved through programming methods. The polarity of the coil potential is fixed and not allowed to toggle once the diode has been forward biased, thereby eliminating the numerical instability caused by the discontinuous behavior of the diode. Electromagnetic energy is allowed to dissipate until the magnitude of the coil potential is insufficient to sustain a forward bias condition. This method provides robust modeling of inductive behavior and eliminates the undesired effects of digital sampling.

This chapter has described numerical methods employed to facilitate simulation of a brushless dc motor on a personal computer. Model development has focused primarily on electronic commutation and power conditioning. The task of buffering the voltage transient behavior associated with commutation switching is investigated in Chapter III.

III. TRANSIENT RESPONSE WAVESHAPING

A. BACKGROUND

Relatively minor adaptations to the power conditioning model developed by MacMillan and illustrated in Figure 2.2 result in dramatic variation of the electronic environment to which the solid state components are subjected. In general, modifications which limit hazardous voltage conditions at the power transistors during commutation switching restrict the motor's overall torque capability.

Stiff current characteristics indicate exaggeration of the transient voltage response acting on solid state devices. Refinement and reshaping of the phase current waveforms may be undertaken with the prospect of minimizing adverse voltage effects.

Modifications to power conditioning circuitry is investigated in this chapter using step velocity response characteristics of the brushless dc motor. Unidirectional kinematics associated with open loop behavior facilitate response waveshaping without the complication of rotational reversal.

B. COMMUTATION ADVANCE & RETARD

The switching logic detailed by Thomas in [Ref.1] for motor rotation in clockwise and counterclockwise directions is summarized in Table I. This logic assumes maximum torquing conditions; that is, the rotor is located in such a position that its field flux is orthogonal to the stator's electromagnetic field. Hall-effect sensors are used to provide quantized rotor position information to the power conditioner for generation of sequencing logic.

TABLE I

SENSOR AND SWITCHING LOGIC

Rotor	RPS			Clockwise						Counterclockwise					
Position	A	B	C	Q1	Q2	Q3	Q4	Q5	Q6	Q1	Q2	Q3	Q4	Q5	Q6
0-30°	1	0	1	0	0	0	1	1	0	0	0	1	0	0	1
30-60°	1	0	0	1	0	0	1	0	0	0	1	1	0	0	0
60-90°	1	1	0	1	0	0	0	0	1	0	1	0	0	1	0
90-120°	0	1	0	0	0	1	0	0	1	0	0	0	1	1	0
120-150°	0	1	1	0	1	1	0	0	0	1	0	0	1	0	0
150-180°	0	0	1	0	1	0	0	1	0	1	0	0	0	0	1

Deviation from this orthogonal relationship may be accomplished by either advancing or retarding commutation. Displacement in relative angular position between the electromagnetic field and the field flux is attainable through modification of the commutation sequencing logic.

Figures 3.1 through 3.6 describe the motor's electrical response characteristics when commutation is advanced and retarded. Operational reliability of the motor, which is largely influenced by the voltage conditions experienced by power conditioning electronic components, must be considered when maximizing its mechanical performance. Numerous

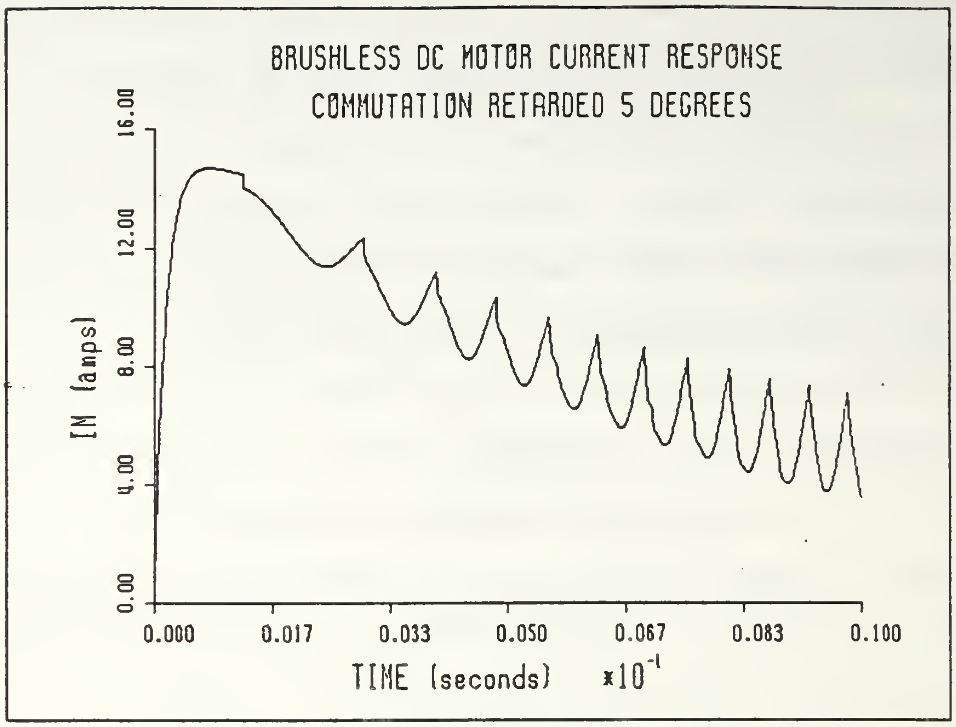


Figure 3.1 Motor Current Response (Commutation Retarded 5°)

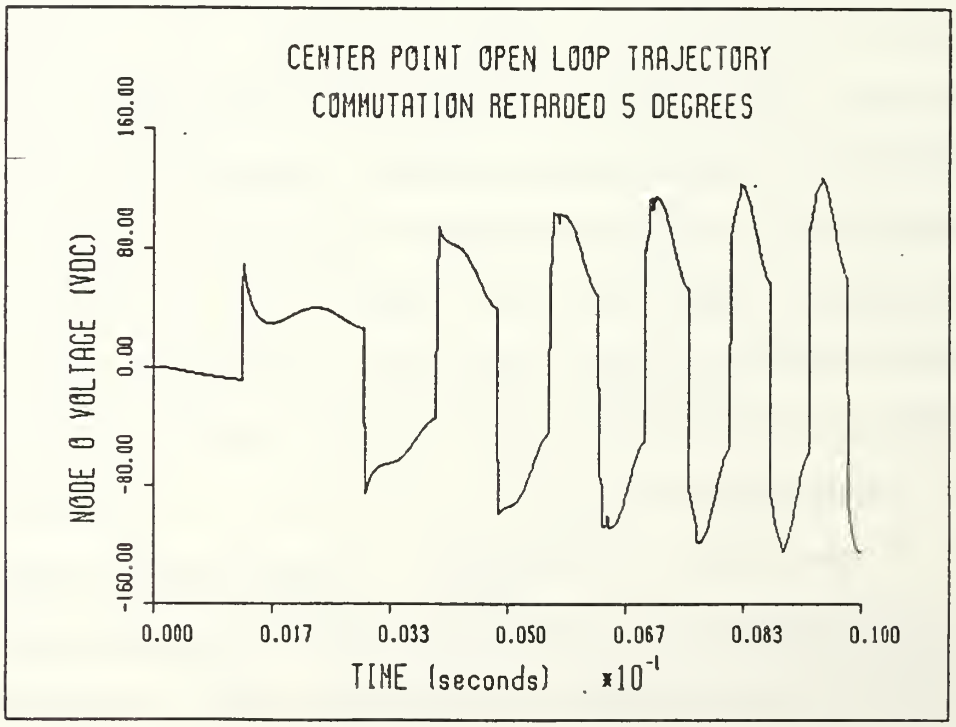


Figure 3.2 Center Point Trajectory (Commutation Retarded 5°)

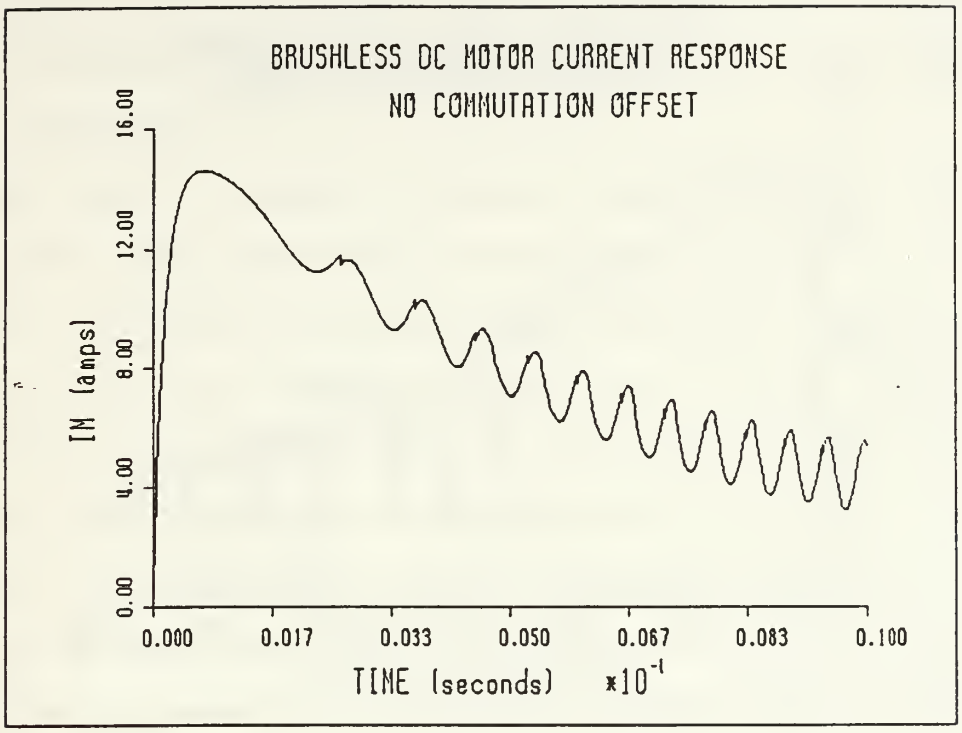


Figure 3.3 Motor Current Response (No Commutation Offset)

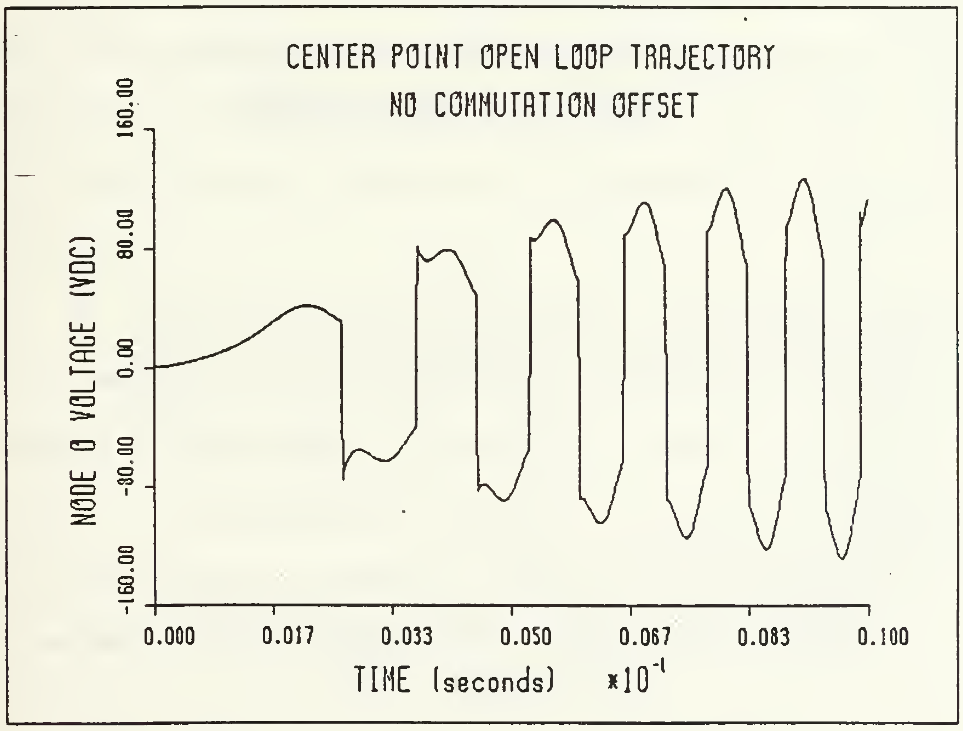


Figure 3.4 Center Point Trajectory (No Commutation Offset)

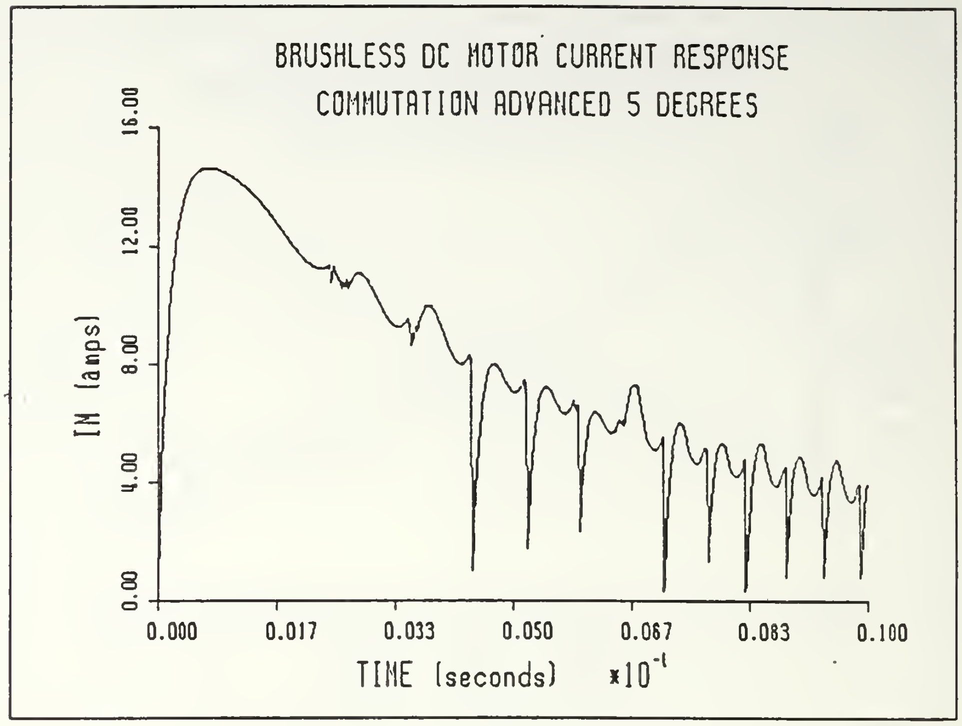


Figure 3.5 Motor Current Response (Commutation Advanced 5°)

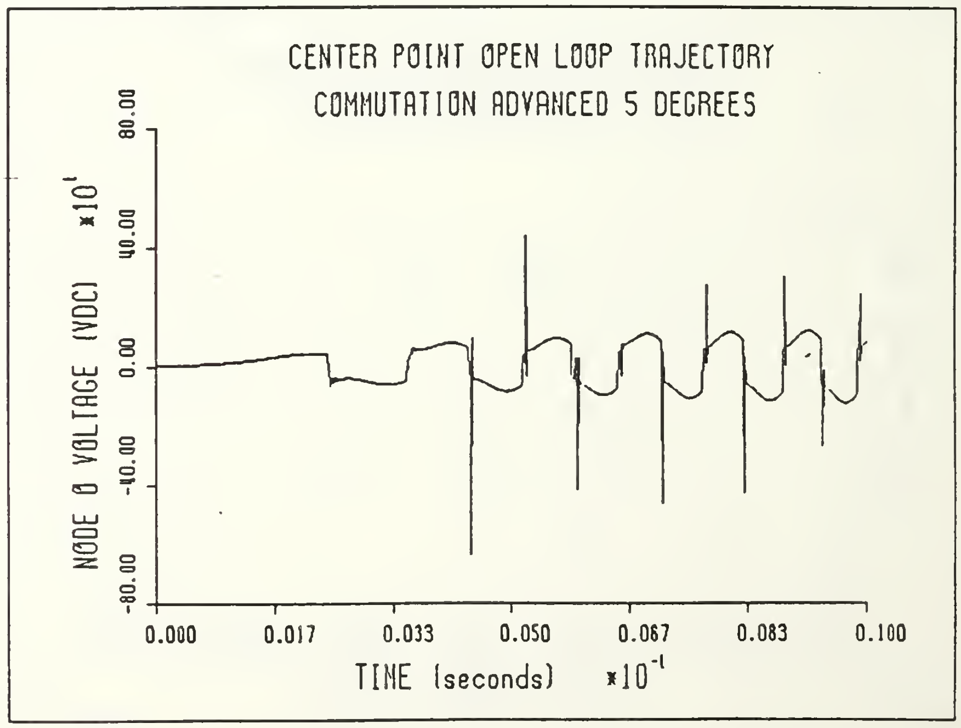


Figure 3.6 Center Point Trajectory (Commutation Advanced 5°)

simulations with varying degrees of commutation advance and retard indicate maximum system responsiveness at orthogonal field conditions.

The free floating center connection of the wye configured model (Node O in Figure 2.2) serves as a common voltage node for the three phase network. This node is offset from its nominal value of 0 volts when load distribution of the network is unbalanced. The trajectory of the center connection is determined by Kirchoff's voltage law and is a function of the generated back emf, phase current through the field windings, and the inductive coil potential. Back emf is predictable under most load conditions and may be uncoupled from the effects of the coil. The trajectory provides a comprehensive indication of voltage transient behavior in the motor during commutation. Minimization of the trajectory's peak voltage values will reduce high voltage conditions experienced by the power transistors.

It is of particular interest to compare the step velocity center point trajectory shown in Figure 3.4 with the response determined by MacMillan and given in [Ref.2, Fig.5.8]. A fundamental premise of MacMillan's model is that the three phase network behaves in a symmetric fashion. This assumption permits the center point trajectory to be trajectory to be described solely in terms of magnetic flux and ignores the cummulative effects of the inductive coil.

Fin step velocity transient response characteristics provide an appropriate means of quantizing the general responsiveness of the motor. Even during the most demanding periods of flight control, fin actuation dynamics are contained within the initial transient response of the open loop configured velocity device. A mechanical performance factor describing fin positioning responsiveness may be determined by computing the normalized average slope of the fin velocity step response measured between 0 and 60% of steady state velocity. Figure 3.7 illustrates the quantization of mechanical performance of a brushless dc motor with no commutation offset.

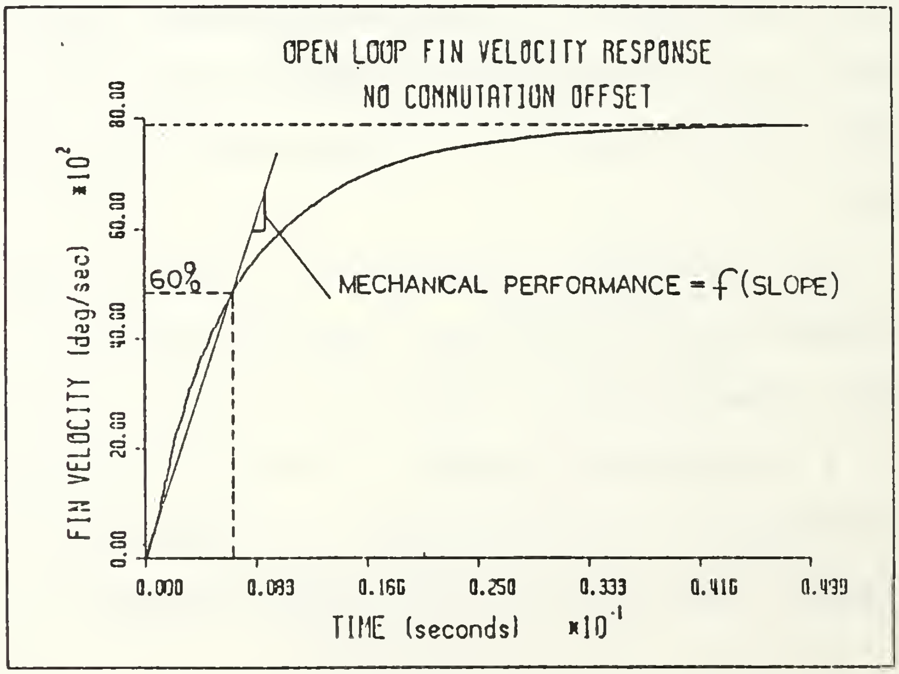


Figure 3.7 Mechanical Performance Factor Description

Electrical performance is well described by the motor's center point voltage response. The transient effects of commutation switching and back emf generation characterize the trajectory. Excessively high voltage conditions observed at the center connection correspond to unacceptable behavior at the power transistors. Therefore, electrical performance is quantized by normalizing average peak values of the center point trajectory.

Figure 3.8 illustrates the relationship between commutation offset and electrical-mechanical performance of the brushless dc motor for ±30° of commutation offset angle. Commutation at orthogonal field conditions provides maximum system responsiveness, which degrades in a somewhat symmetrical manner as advance and retard angles are increased.

Center point trajectory peak voltage values in excess of 500 volts are illustrated in Figure 3.6. Therefore, the unacceptable electrical response behavior associated with advanced commutation invalidates its application in this design. Additionally, significant retarding of commutation is required to noticeably reduce the high voltage conditions associated with commutation switching. Because of the substantial compromise in performance at these retarding offsets, neither commutation advancing nor retarding was deemed advantageous and, therefore, not implemented.

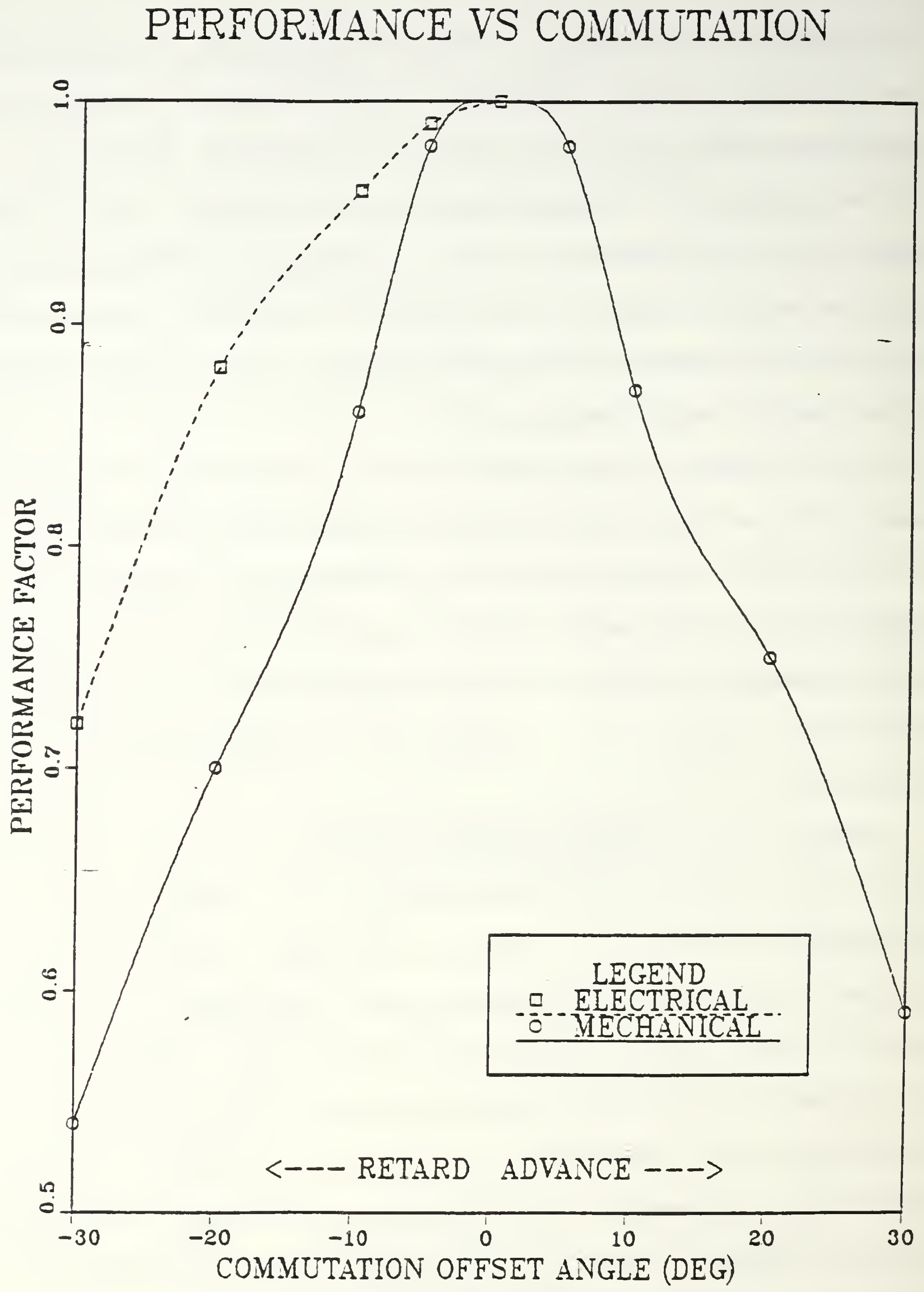


Figure 3.8 Electrical-Mechanical Performance vs Commutation

C. DIODE BIAS THRESHOLD

The demanding operating conditions encountered by the brushless dc motor in service necessitate current limiting protection. Previous models have provided this protection with a relatively large power supply series resistance. Fluctuations in load and general performance of the motor are comfortably absorbed using such a method of current limitation. However, the scheme reduces motor supply line voltage to an unacceptably low level with respect to biasing threshold requirements of the protective diodes. Even though protective diodes are functioning properly during commutation switching, stiff current conditions are observed near the peaks of current ripple in the response shown in Figure 3.3. During cyclic conditions of maximum emf generation, protective diodes are falsely forward biased due to insufficient line voltage. Random diode triggering may short- active circuits and result in abrupt behavior in current and voltage responses.

Modification of the 3-phase model shown in Figure 2.2 allows for the same value of equivalent supply resistance to be divided in series across each transistor-diode pair and is illustrated in Figure 3.9. The reconfiguration permits selection of the voltage divider relationship necessary for correct triggering of the protective diodes during commutation switching and maintains a viable means of current limiting protection through series resistance.

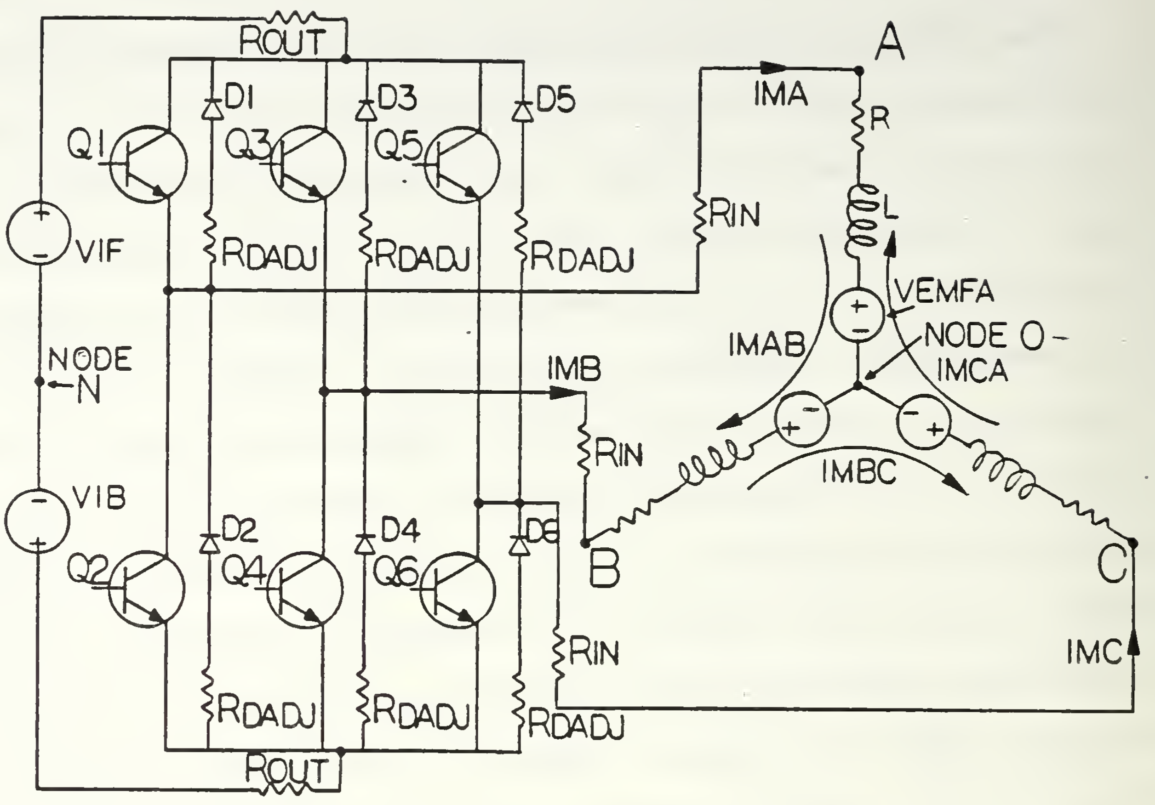


Figure 3.9 Modified 3-Phase Bridge Circuit

Voltage divider percentage is determined by Equation 3.1.

$$\text{Voltage Divider \%} = R_{in} / (R_{in} + R_{out}) \qquad (3.1)$$

Figures 3.10 through 3.15 illustrate the effects on current and voltage response when the free-wheeling diode's bias threshold is varied by voltage divider adjustment. As observed in Figure 3.3, insufficient bias threshold results in unexpected diode firing and short circuiting of the affected phase. On the other hand, excessive bias threshold conditions, such as the 63% voltage divider configuration illustrated in Figures 3.10, 3.12, and 3.14, result in premature cutoff of the protective diodes during free-wheeling conditions. The electromagnetic energy stored in the coil is not sufficiently dissipated through a low resistance path and high voltage conditions are observed across the power transistors in Figure 3.14. It is interesting to note that excessive bias threshold conditions preclude forward biasing of protective diodes during only a single switching operation as illustrated in Figure 3.10 at t=2.5msec. This is explained by the velocity dependence of back emf. At lower speeds, the inductive coil is insufficiently supplemented by back emf generation to forward bias the protective diode. At higher speeds, however, back emf generation is significant and adequately contributes towards satisfying diode triggering criteria. A 50% voltage divider ensures robust diode operation and provides effective current limiting. The corresponding electrical transient characteristics of this configuration are depicted in Figures 3.11, 3.13, and 3.15. Figure 3.15 clearly indicates reduction of the peak voltage accross the transistor.

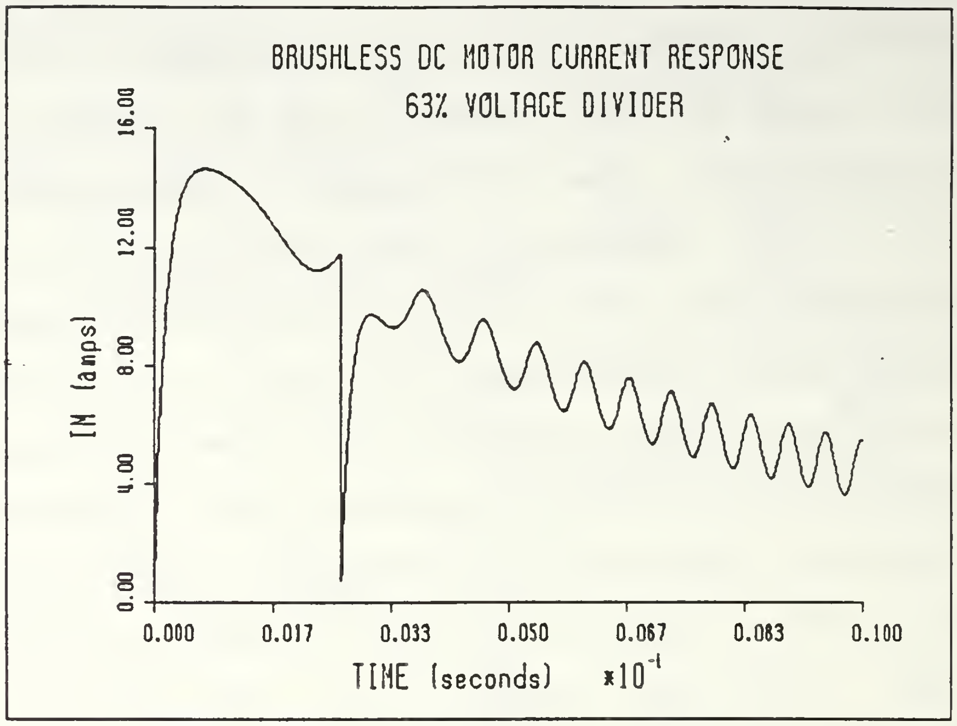


Figure 3.10 Motor Current Response (63% Voltage Divider)

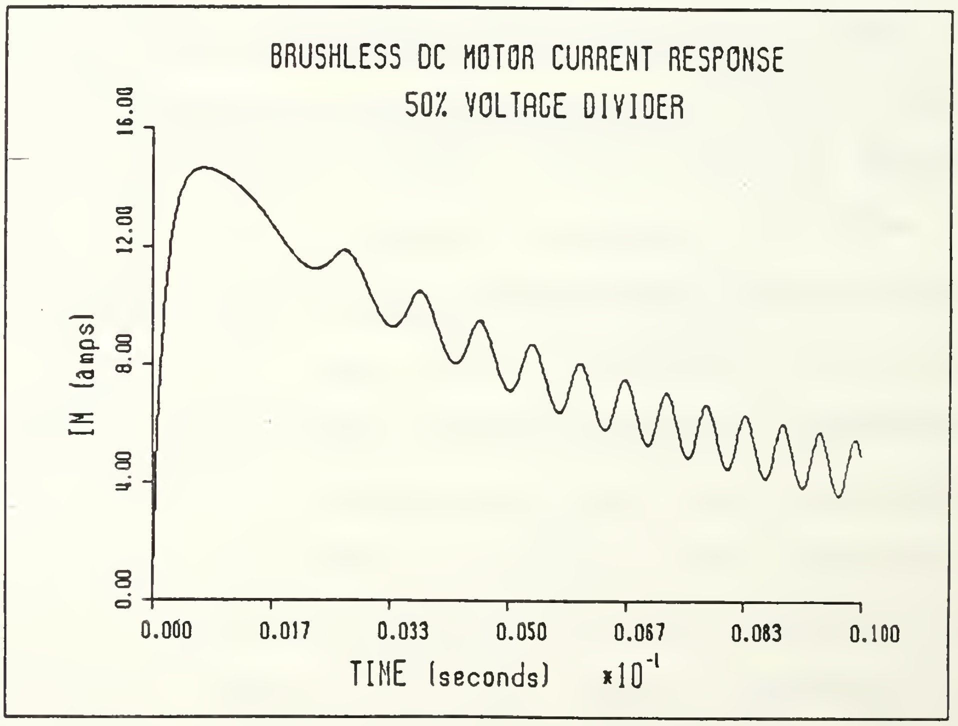


Figure 3.11 Motor Current Response (50% Voltage Divider)

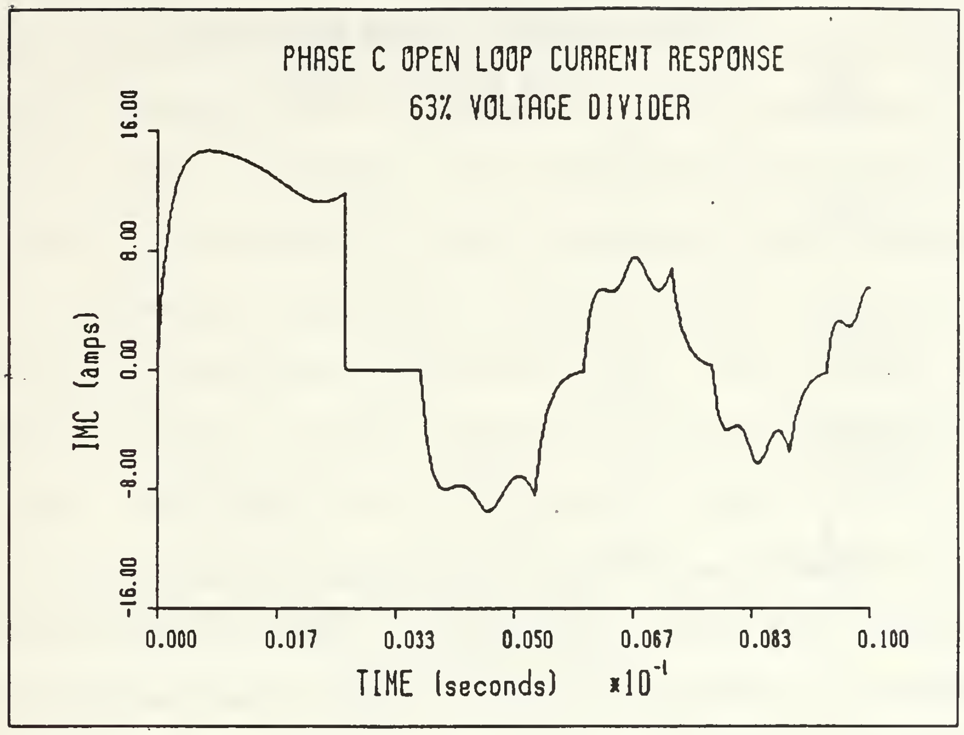


Figure 3.12 Phase Current Response (63% Voltage Divider)

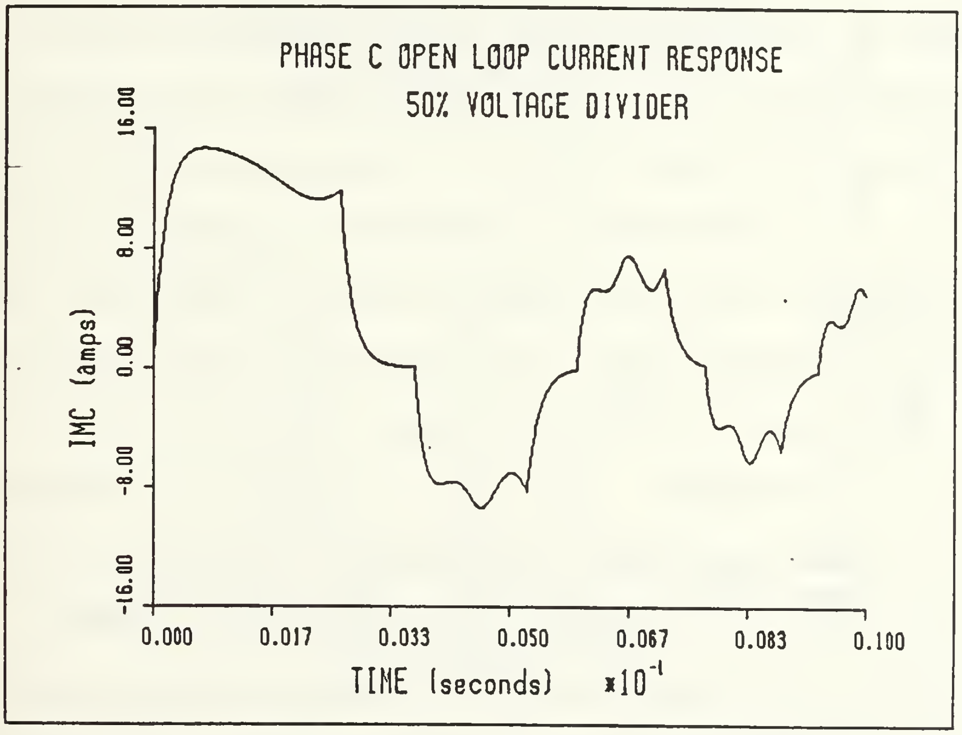


Figure 3.13 Phase Current Response (50% Voltage Divider)

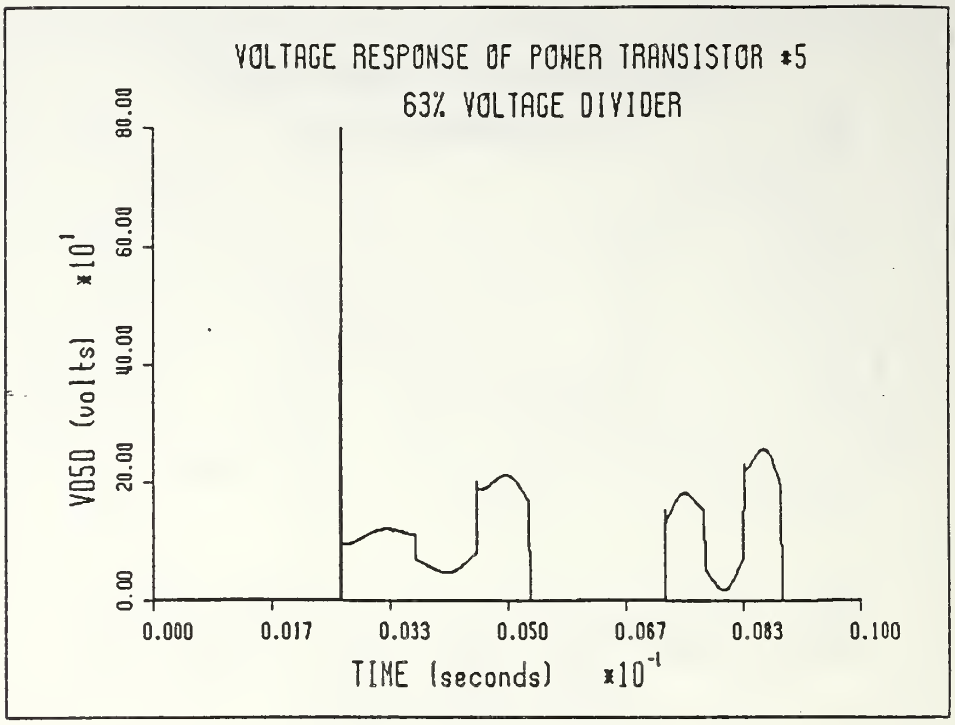


Figure 3.14 Transistor #5 Voltage Response (63% Voltage Divider)

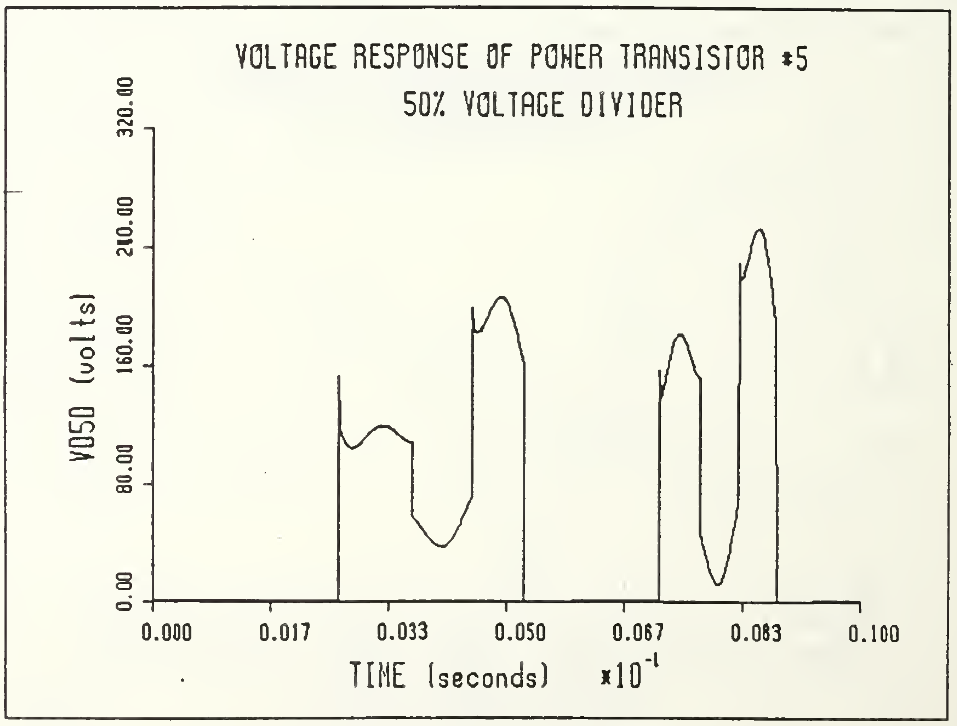


Figure 3.15 Transistor #5 Voltage Response (50% Voltage Divider)

D. CURRENT DECAY TIME CONSTANT

The exponential decay of current in a relaxing phase is described uniquely by a dynamic time constant. The circuit's time constant is determined by the phase inductance, L, divided by its equivalent path resistance. Previous modeling provides either high or low path resistance conditions determined by the state of the protective diode. A high resistance state yields extremely fast time constants which results in high di/dt values. Conversely, the low resistance state is described by a relatively slow decay transient. If the transient's duration exceeds the time required for 30° of mechanical rotation, then the remaining electromagnetic energy stored in the coil will be exponentially dissipated with the fast time constant. This condition is characterized by undesired high voltage transients across the power transistors and is found to be more prevalent at higher operating speeds where less time for energy dissipation is available.

The simulation program is provided with an adjustable resistance placed in series with each protective diode to permit control of the phase current's decay time during free-wheeling. Location of the adjustable resistance (RDADJ) in the power conditioning model is given in Figure 3.9. Average response characteristics of the motor are unaffected by this added resistance since it is negligible when compared to the equivalent loop resistance. However, RDADJ dominates the current decay return path resistance and essentially determines the circuit's time constant. Physical implementation is feasible since the added resistor is external to the motor and actually a component of the power conditioner.

Figures 3.16 through 3.21 graphically depict the waveshaping effects of RDADJ on phase current and transistor voltage. Selection of the rate adjusting resistance is a fairly straightforward task since it is clearly bounded by its consequences. Increased decay rate results from increasing the resistance (RDADJ) and corresponds directly to higher voltage transients at the power transistors. Figures 3.18 and 3.19 illustrate the intolerable consequences associated with the selection of a very fast time constant. A 3Ω resistance for RDADJ improves the decay time constant significantly with an increased but acceptable transistor voltage transient peak, which is shown in Figure 3.21.

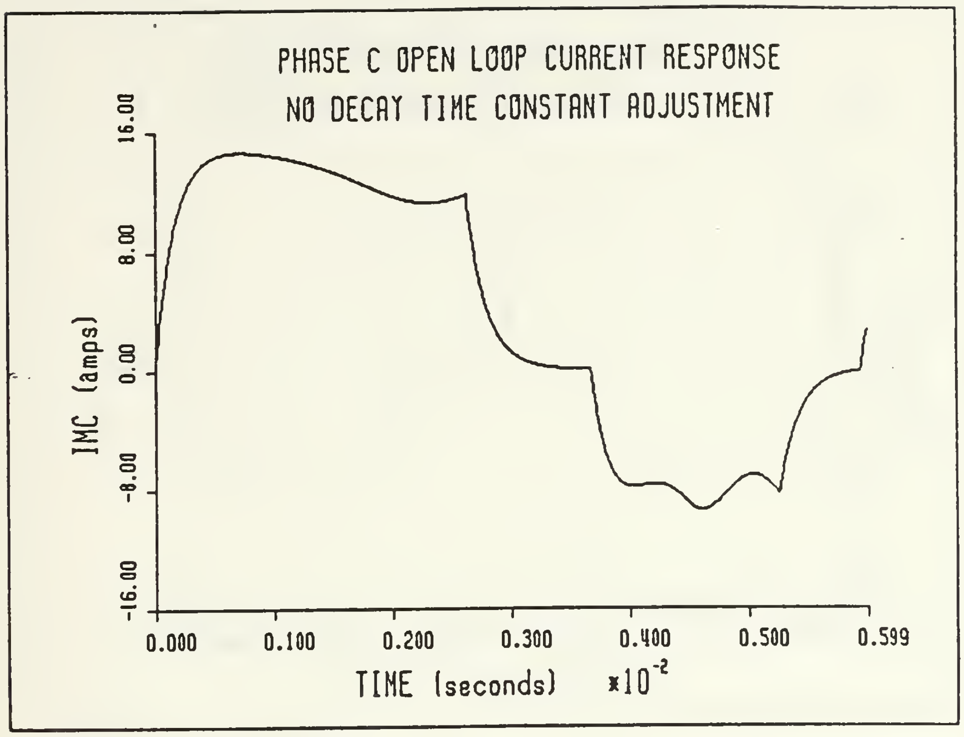


Figure 3.16 Phase C Current Response (RDADJ = 0Ω)

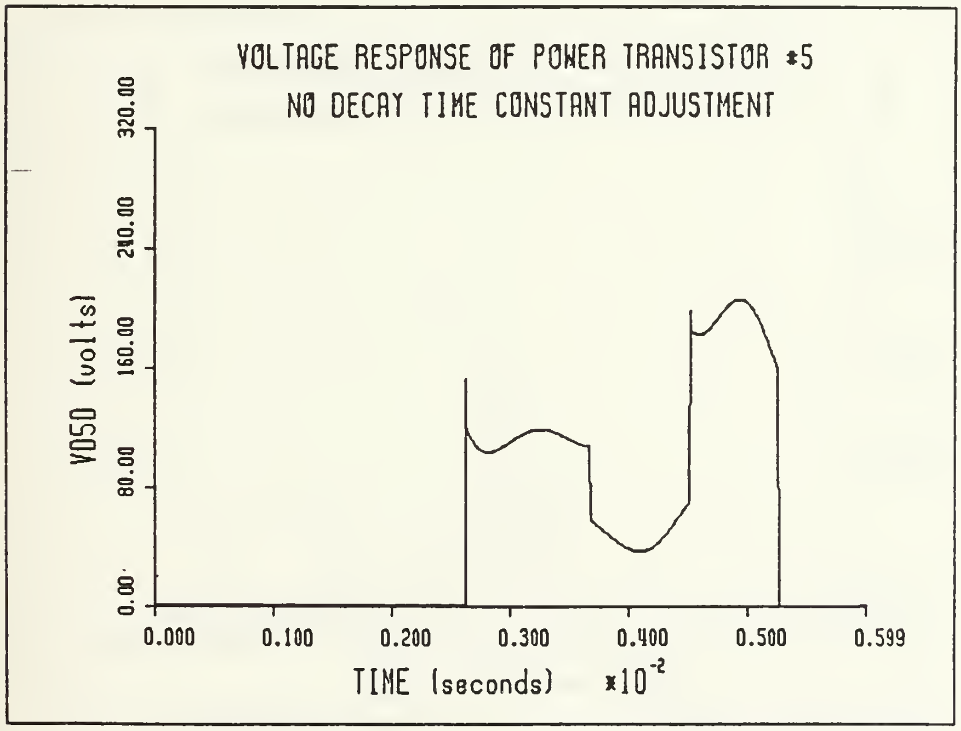


Figure 3.17 Transistor #5 Voltage Response (RDADJ = 0Ω)

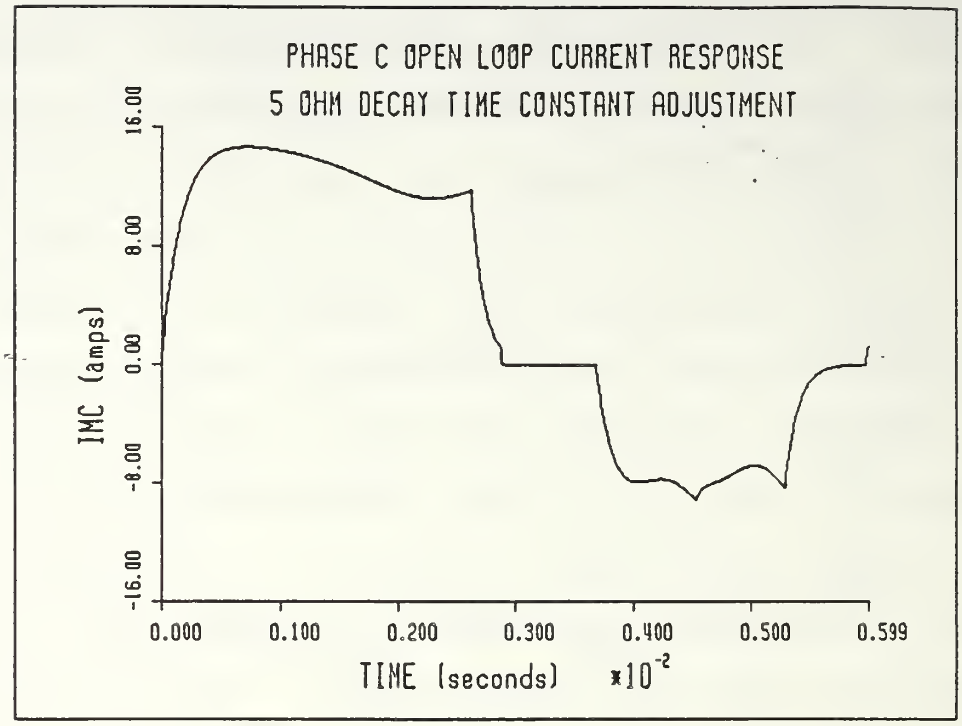


Figure 3.18 Phase C Current Response (RDADJ = 5Ω)

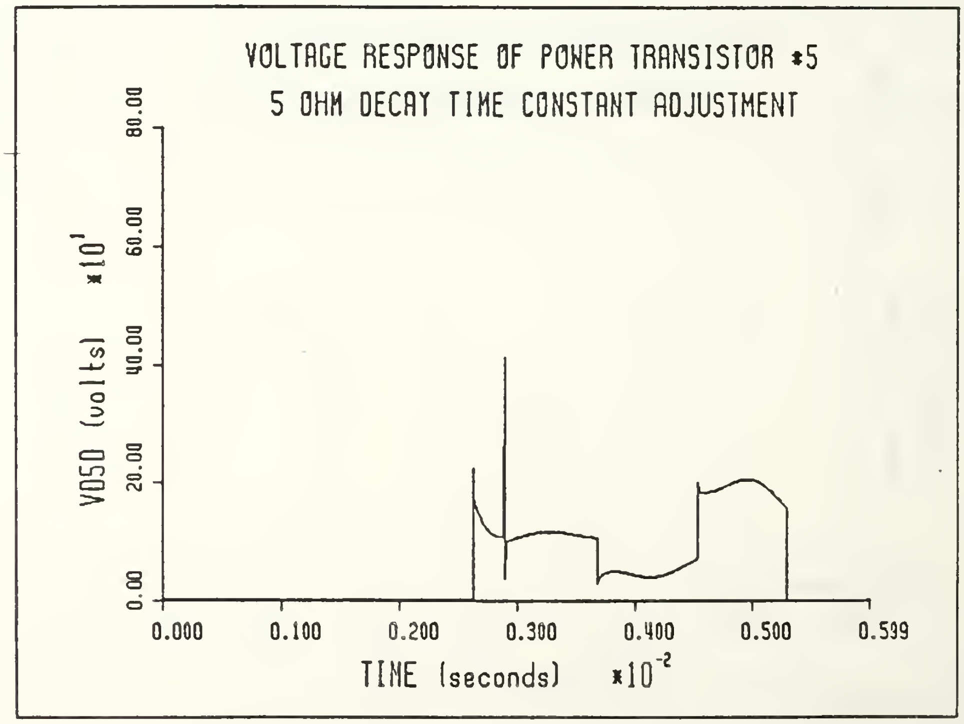


Figure 3.19 Transistor #5 Voltage Response (RDADJ = 5Ω)

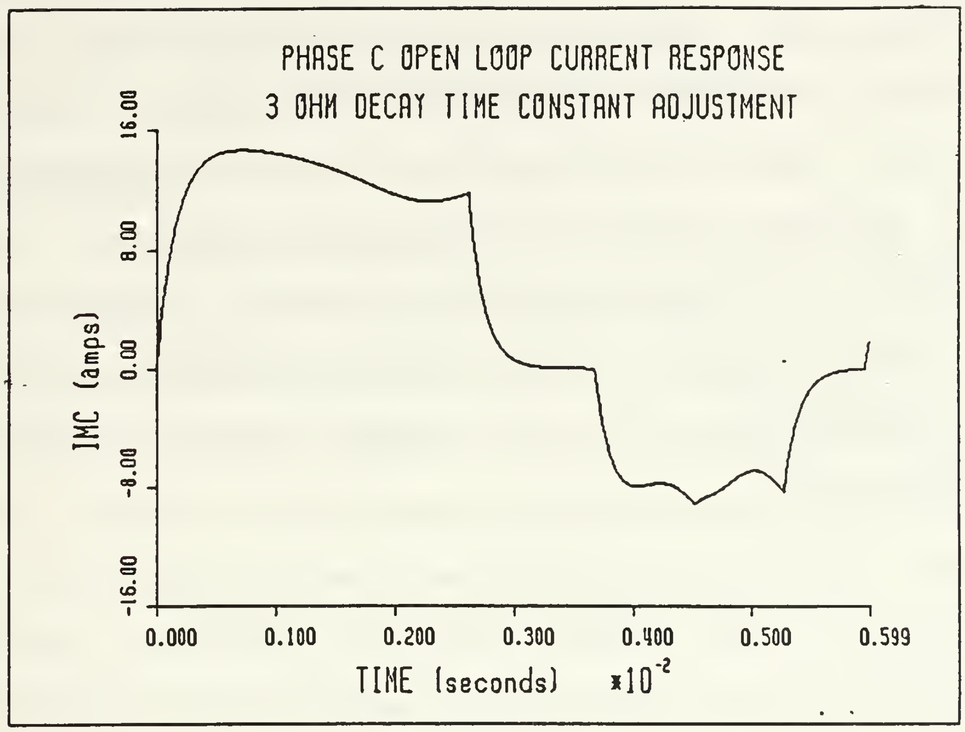


Figure 3.20 Phase C Current Response (RDADJ = 3Ω)

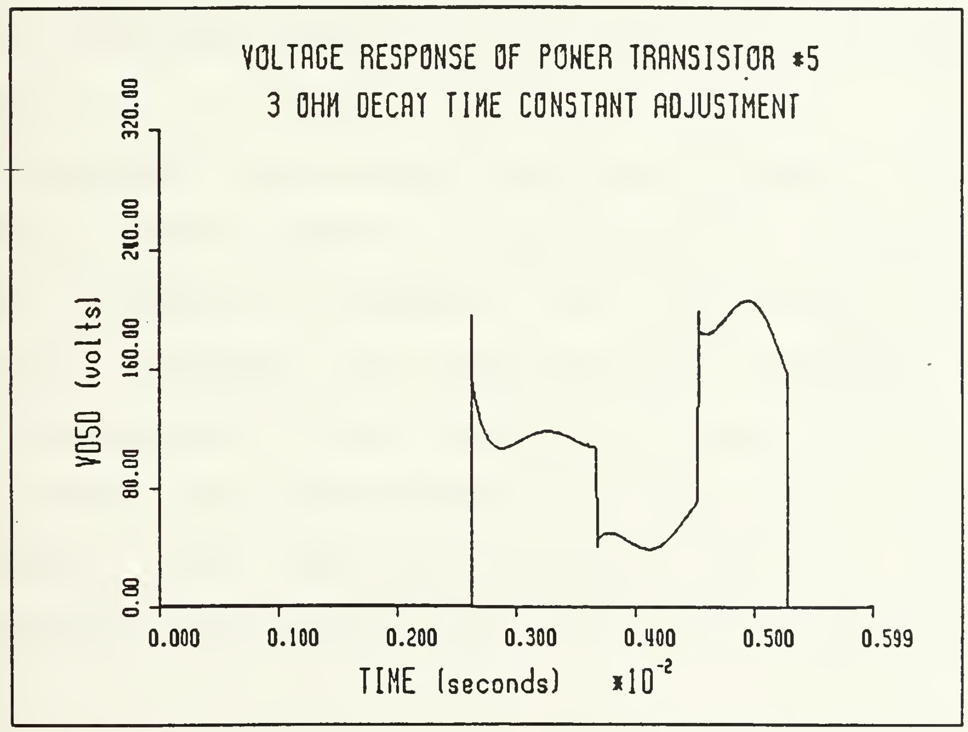


Figure 3.21 Transistor #5 Voltage Response (RDADJ = 3Ω)

Step velocity response waveshaping has been exploited to optimize the transient characteristics of the brushless dc motor and its associated electronic commutation circuitry. Many of the benefits of such refinement are not readily apparent during unidirectional rotation. However, the highly accentuated transient behavior associated with closed loop position control is significantly affected by these modifications and will receive further attention in the Chapter IV.

IV. CLOSED LOOP CONSIDERATIONS

A. BACKGROUND

NPS studies of brushless dc motors primarily support variable speed control applications [Refs. 1,2,6,7]. Very limited documentation concerning its viability in closed loop position control appears in the referenced literature. Previous research at NPS has also been restricted mainly to open loop (velocity) performance characteristics. However, brushless dc motor cruise missile fin control was investigated and simulated by Franklin using an equivalent lumped parameter model [Ref.7]. Additionally, MacMillan's detailed model provides rudimentary observation of motor current transient behavior when rotational direction is reversed.

In addition to the unidirectional kinematics normally associated with variable speed control, closed loop position control includes such conditions whereby mechanical rotation and electrically developed torque oppose each other. The intention of this chapter is to study closed loop positioning characteristics of brushless dc motors, with particular emphasis on the transient behavior associated with reversing rotational direction.

B. CLOSED LOOP MECHANICS

The mechanics of position control of a permanent magnet dc motor are broadly described by three electromechanical conditions. The natural operational state of a working dc motor is known as *motoring*. This condition is characterized by electrical to mechanical energy conversion and occurs when the motor is driven between zero and steady state speeds. When the motor is forced to rotate at a greater rate than its steady state speed either by external disturbance or decreased supply voltage, generator action is realized. *Generation* converts mechanical to electrical energy and, if suitably configured, can be used to replenish the power supply through regeneration. The mechanical energy consumed in electrical regeneration dynamically brakes motor rotation and provides increased deceleration during relaxation conditions. The third operational state is *forced braking* and occurs when the motor is forced to rotate against its present direction. Associated with the resulting intense rotational deceleration are electrical transients that are accentuated and often result in destructive magnitude of current through and voltage across the power transistor/diode pair. [Ref.8]

C. FOUR QUADRANT OPERATION

The electronic commutation of a three phase, 4-pole brushless dc motor configured for position control may be more comprehensively described as *four quadrant operation* [Ref.9]. Following in similar manner, Figure 4.1 illustrates the electromechanical conditions describing the four quadrants. Electromagnetic field orientation determines the electrically developed torque, T, which forces rotation in a prescribed direction. This torquing direction is denoted by the variable "DIR" in the computer simulation and is accomplished through logic sequencing of the power transistors. Actual mechanical rotation, ω, describes the kinematic state of the rotor.

The transient dynamics involved in attaining positional steady state may be classified as forward motoring, forward braking, reverse motoring, and reverse braking. Except for directional differences, response characteristics of forward and reverse motoring are symmetric, as are those of forward and reverse braking. As shown in Figure 4.1, reversal of commutation direction may be buffered by generator action if any degree of system relaxation is provided by the controller.

Quadrants II and IV of Figure 4.1 describe motoring conditions, where actual mechanical rotation (ω) and electrically developed torque (T) are in the same direction. During this mode of operation, response characteristics are electrically similar to unidirectional, open loop behavior. Transient conditions are relatively well behaved since protective diodes are able to dissipate electromagnetic energy stored in relaxed phase inductive coils as intended. The back emf generated while motoring converts the mechanical energy of rotation to electrical energy proportional to the speed of rotation and is opposite in polarity of the forcing potential. The superposition of source and generated voltage net a reduced electromotive force and, therefore, impede and eventually limit the motor's rotational rate.

Forced braking immediately follows the reversal of electronic commutation and is illustrated in quadrants I and III of Figure 4.1. This condition is commonly referred to as *plugging* in a brush-type motor and occurs when the applied voltage is reversed in polarity. Plugging of brushless dc motors is accomplished through commutation logic sequencing, since supply voltage polarity is fixed. Consider the lightly damped fin angle stepped response also shown in the figure. When the forward running motor comes to zero speed under braking action at $t=t_1$, it automatically gets accelerated in the reversed direction since the commutation logic for forward braking and reverse motoring is identical. While rapid braking and reversing characteristics are desired in a position control system, the exaggerated transient behavior of the motor is electronically demanding and may result in damage to solid state devices.

Figure 4.1 also indicates the presence of generator action immediately adjacent to commutation reversal. If the controller provides suitable conditions for natural response of the motor, energy is converted by regenerative processes and dynamic braking is attained. Controllers which operate with a dead zone or have soft response characteristics often promote generator action and are associated with better behaved transients. Conversely, stiff controllers with no dead zone, such as an ideal relay, do not experience natural response conditions when plugged. Therefore, the buffering effect provided by dynamic braking is not exploited by high performance controllers and the corresponding electrical response is characterized by excessive transient behavior.

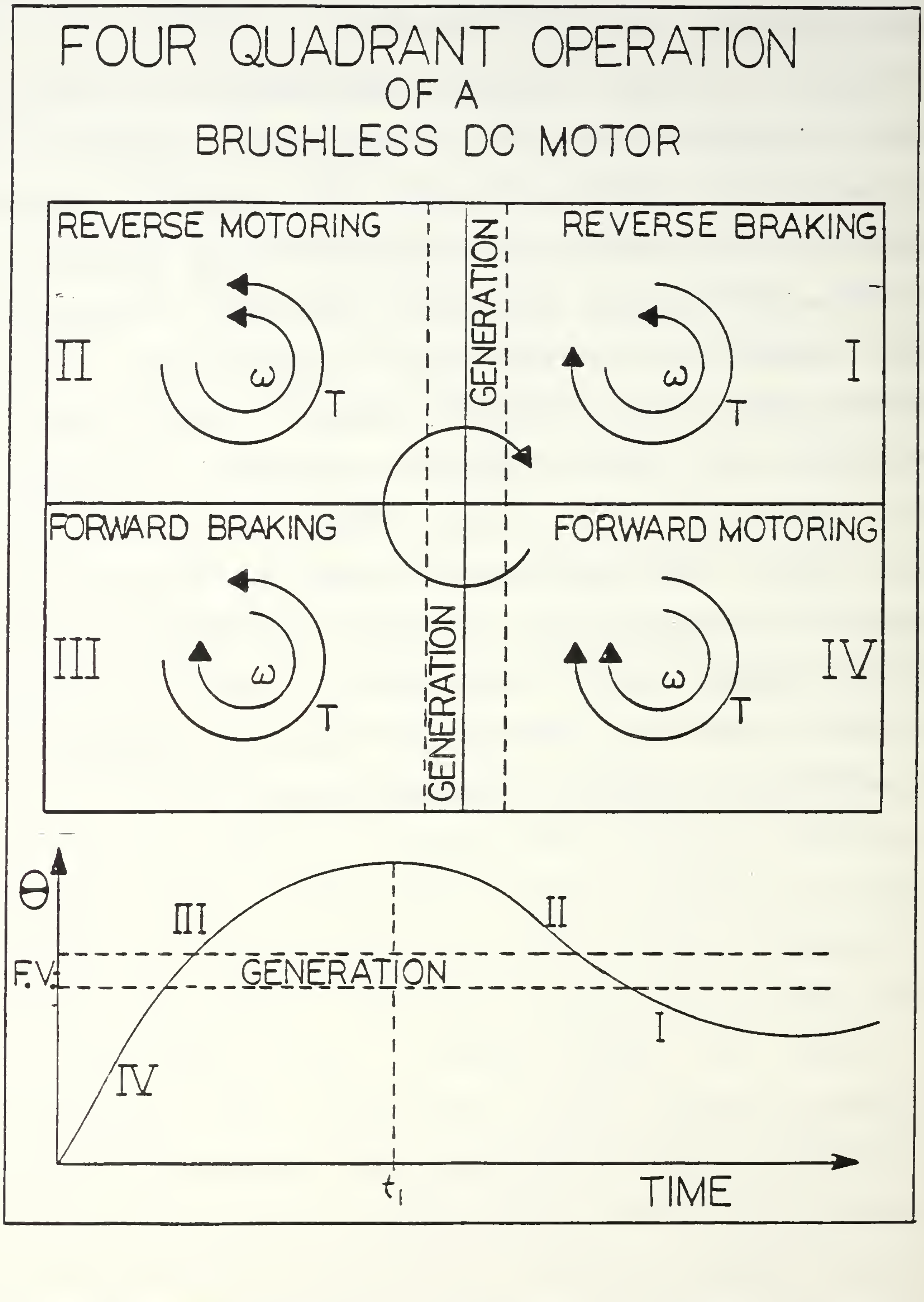


Figure 4.1 Four Quadrant Operation of a Brushless DC Motor

D. TRANSIENT BEHAVIOR

The excessive transient behavior observed during braking is explained by several factors. Generated back emf is now of the same polarity as the forcing potential and the superposition of source and generated voltages net an enhanced electromotive force. The resulting responsiveness of the system, as well as its transient behavior, is increased.

Electromagnetic energy stored in an apparently cutoff phase inductive coil for the three phase, 4-pole motor is intended to be dissipated within the time required for thirty degrees of mechanical rotation. When the motor is initially plugged, less time is likely to be available for decay and high voltage conditions may result.

During forced braking conditions, the direction of actual mechanical rotation (ω) opposes the prescribed commutation logic sequence and results in commutation switching performed in reverse order. This apparent back-stepping through the sequencing logic results in reversal, rather than redirection, of phase current flow within the motor. The effects of rapidly reversing current flow within the motor is significant due to the nature of the inductive coil and result in intolerable voltage transients.

The commutation logic which sequences the switching of power transistors should be sensitive to the controller's mode of operation. While in the forced braking mode, complete transistor switching cannot be performed simultaneously without catastrophic results, and a two step sequence is called for. Stored coil energy in the affected phase should be minimized prior to reversing the direction of the current flow through it. Therefore, a time delay is required between switching off the existing current and switching on the reversing current. During this momentary period of natural response, phase current should be decayed with a reasonable time constant to reduce the voltage transients associated with current reversal. If the commutation delay exceeds the current decay time, near complete dissipation of the energy stored in the coil will be realized and the reversal of current can be performed acceptably.

The rate of decay of electromagnetic energy stored in a relaxed coil is determined by the circuits time constant. The addition of a 3Ω resistance in the decay path, as discussed in Chapter III, provides more rapid dissipation of the stored energy. Less delay time is required for faster decaying current conditions, thereby minimizing system performance degradation during commutation switching. Figure 4.2 depicts a typical first reversal encountered during fin position response when a 10° step of demand is applied using an ideal relay type controller.

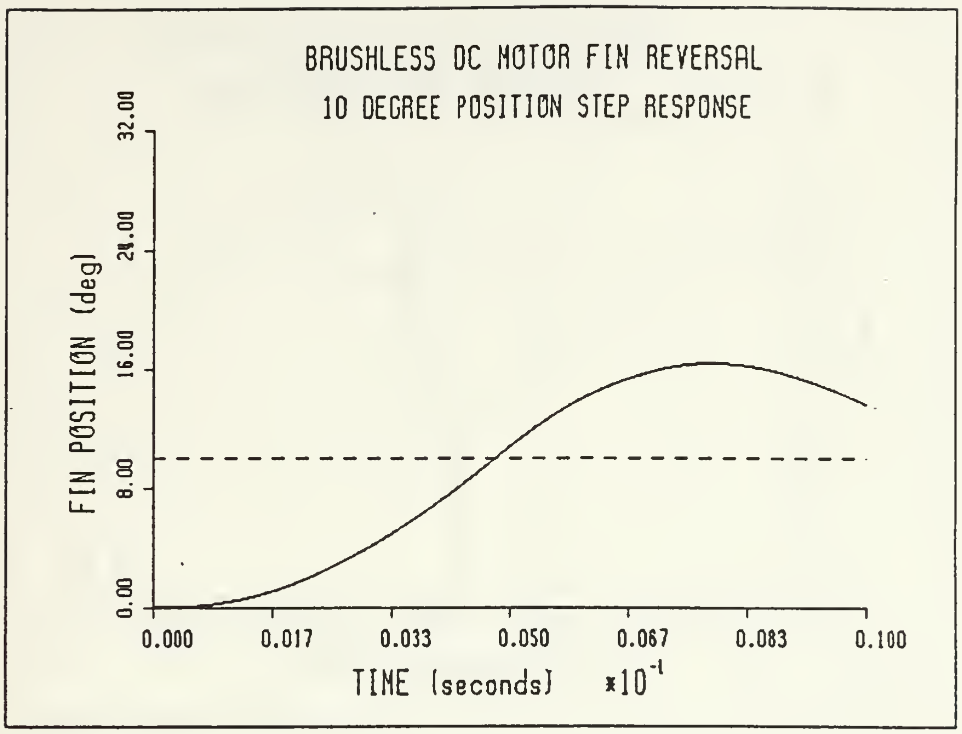


Figure 4.2 Fin Reversal During Position 10° Step Response

The effect on current and voltage waveform of commutation switching delay in fin position control during this reversal is illustrated in Figures 4.3 through 4.6. Transient current behavior and center connection voltage response (Node 0) with no commutation delay applied are shown in Figures 4.3 and 4.5. Current is observed to be decayed very rapidly in Figure 4.3 when plugged due to the nearly instantaneous reversal of phase current. The rapid change in current flow induces very large coil potential, exhibited in Figure 4.5 as a voltage spike in excess of 1000 volts.

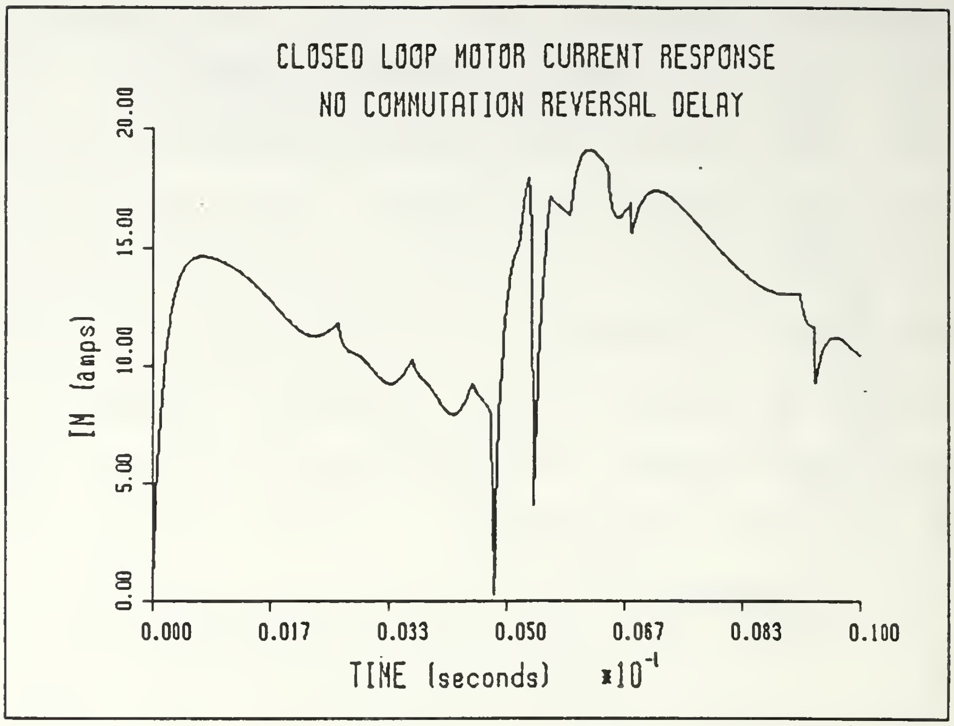


Figure 4.3 Motor Current Response with No Commutation Reversal Delay

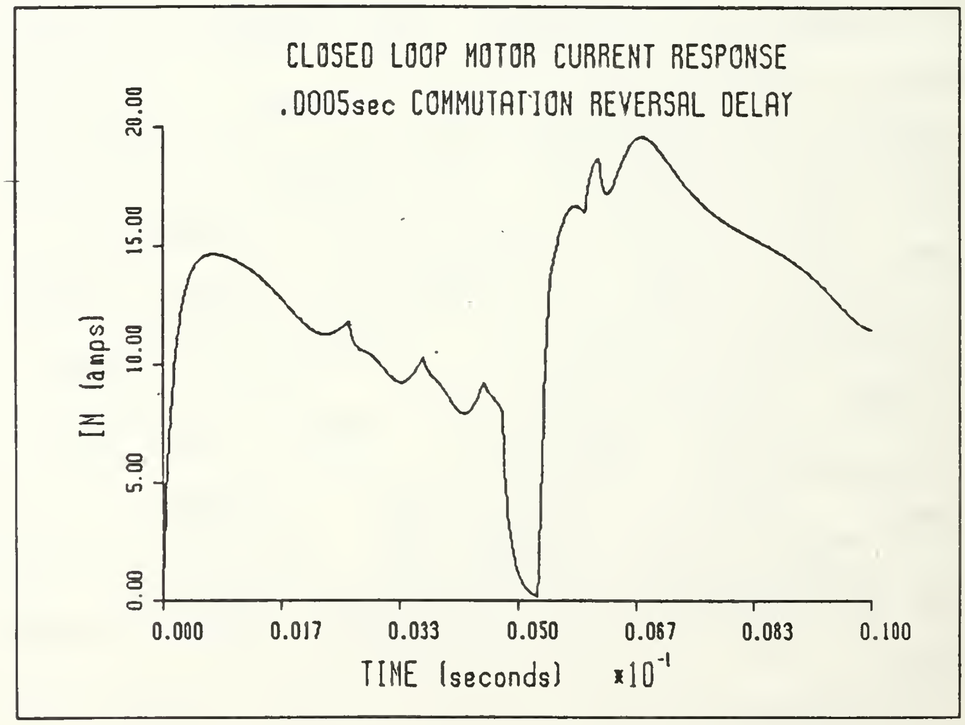


Figure 4.4 Motor Current Response with Commutation Reversal Delay of 500 μsec

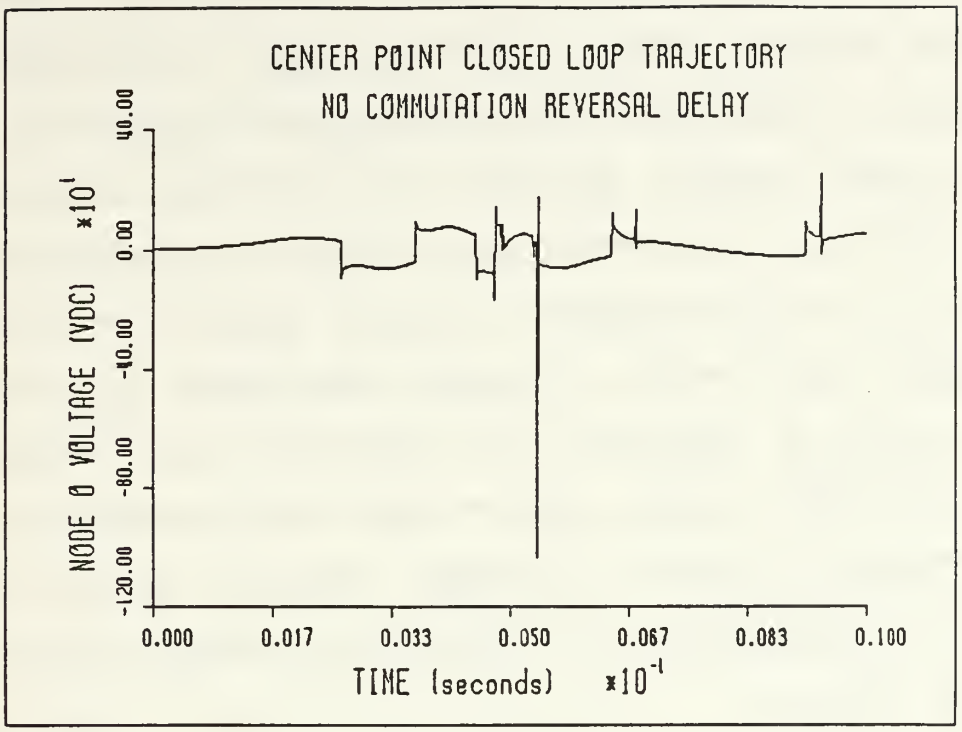


Figure 4.5 Center Point Trajectory with No Commutation Reversal Delay

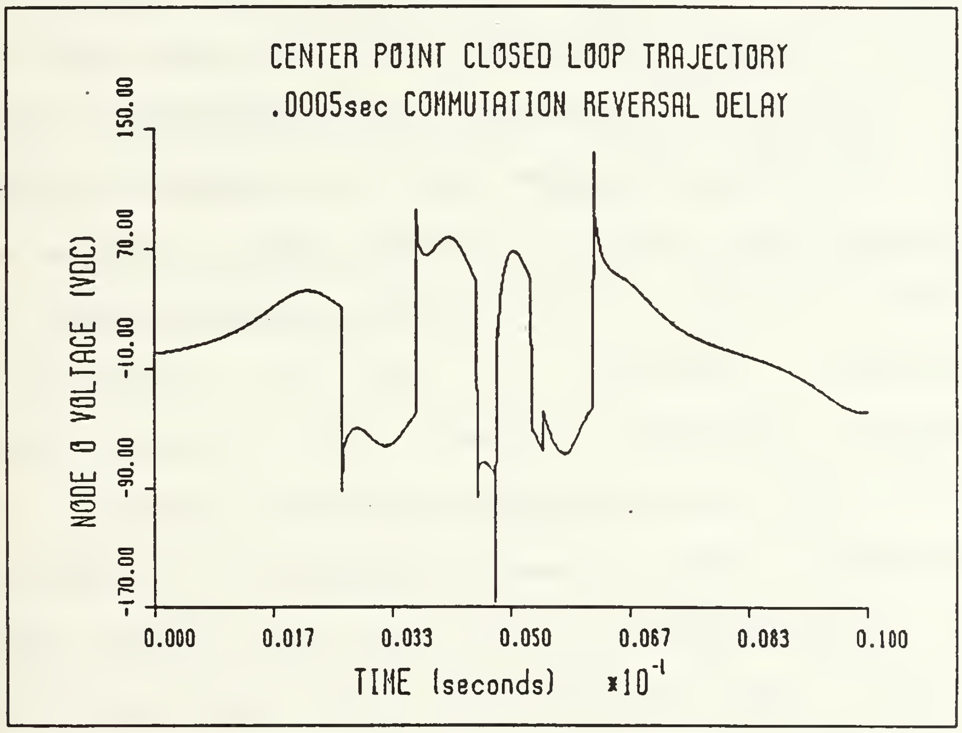


Figure 4.6 Center Point Trajectory with Commutation Reversal Delay of 500 μsec

Figures 4.4 and 4.6 depict much more acceptable response behavior when a 500μsec delay is provided. The exponential decay of motor current shown in Figure 4.4 is much slower, however, and does not completely dissipate the coil energy. A voltage spike of 160 volts is observed in Figure 4.6 and corresponds to the rapid dissipation of remaining coil energy. Complete dissipation of the stored coil energy is apparently not practical, particularly at high rotational rates, due to relatively long decay time requirements. However, voltage transients during braking are minimized by nearly an order of magnitude using a delay time of 500μsec.

In general, highly responsive position control of a brushless dc motor is attained at the expense of its electrical transient behavior. Specifically, the level of energy stored in an inductive coil immediately prior to braking determines the extent of its transient. Extremely stiff controllers, such as an ideal relay, provide maximum electromotive force to the motor at all times during positioning. Figures 4.7 and 4.9 illustrate the unacceptable transient current and voltage behavior associated with the unbuffered bang-bang response. Figure 4.7 indicates a rapid transient behavior of plugged phase current which results in the 1000 volt spike shown in Figure 4.9. The inclusion of a $\pm 2°$ dead zone invokes generator action whose effects are described in Figures 4.8

and 4.10. The relatively large window provided for system relaxation by ±2° dead zone is clearly depicted in Figure 4.8, with current characterized by the dominant effects of back emf and dissipating coil energy. Figure 4.10 indicates a corresponding voltage spike of only 150 volts was induced. A finite amount of stored coil energy was converted to mechanical energy during motor relaxation provided by controller dead zone. However, system accuracy is sacrificed when dead zone is applied and the duration of natural system response required to significantly reduce the high voltage transients is unacceptably large. Additionally, a fixed dead zone which is effective at lower speeds, may not provide sufficient system relaxation at greater rotational rates where less time is required to transit the dead zone. Figure 4.10 shows an increased voltage spike magnitude of 300 volts associated with a higher speed reversal. While dead zone can be used to reduce voltage transients, it is not solely sufficient to ensure acceptable behavior.

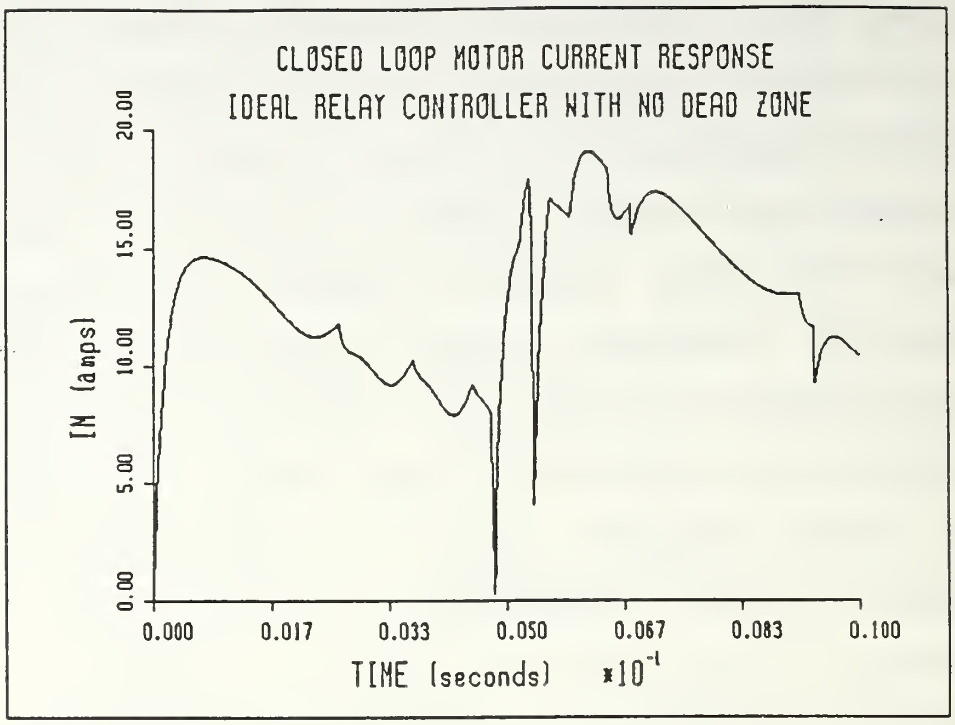


Figure 4.7 Motor Current Response with No Dead Zone

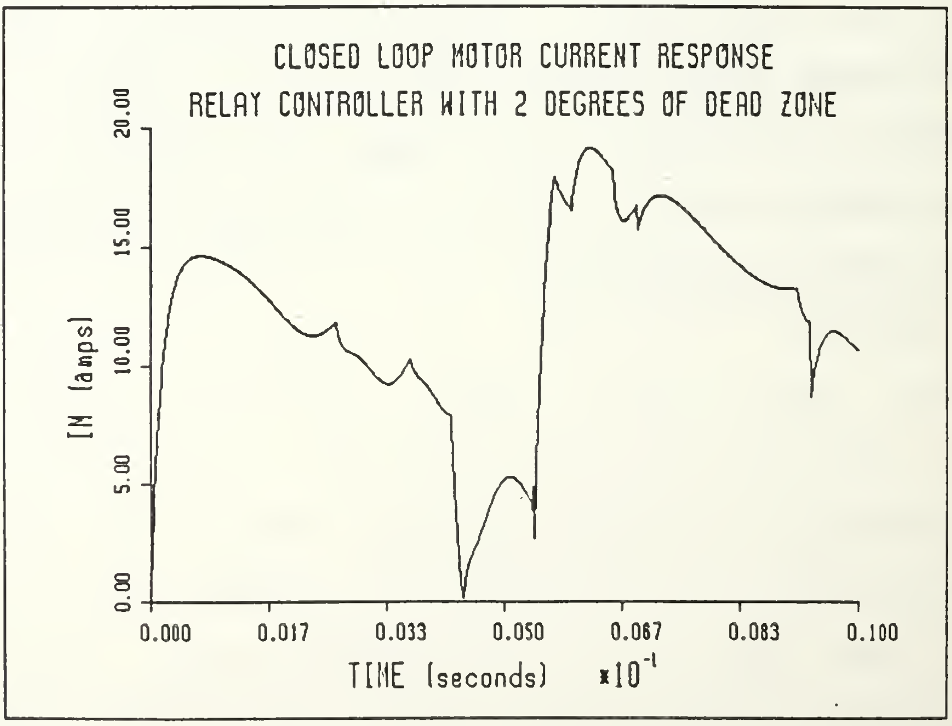


Figure 4.8 Motor Current Response with 2° of Dead Zone

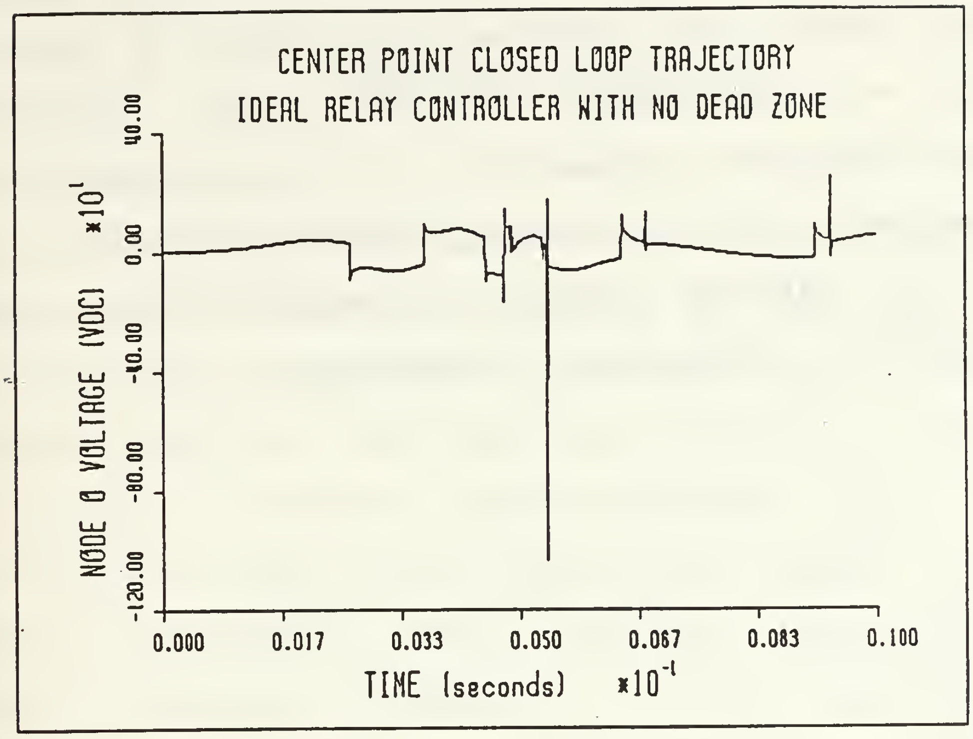


Figure 4.9 Center Point Trajectory with No Dead Zone

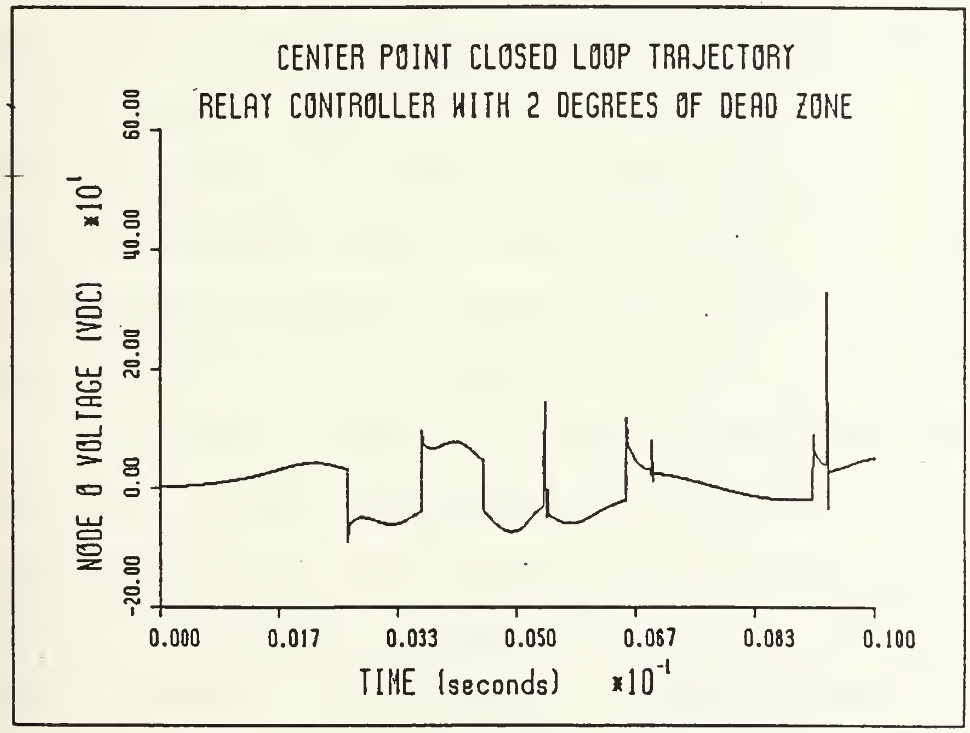


Figure 4.10 Center Point Trajectory with 2° of Dead Zone

It has been shown in this chapter that high performance position control of brushless dc motors is generally attained at the expense of its power conditioning electronic component reliability. In support of the need for responsive fin actuation, reasonable steady state accuracy and buffered electrical transient behavior, pulse width modulation is examined in Chapter V.

V. PULSE WIDTH MODULATION

A. BACKGROUND

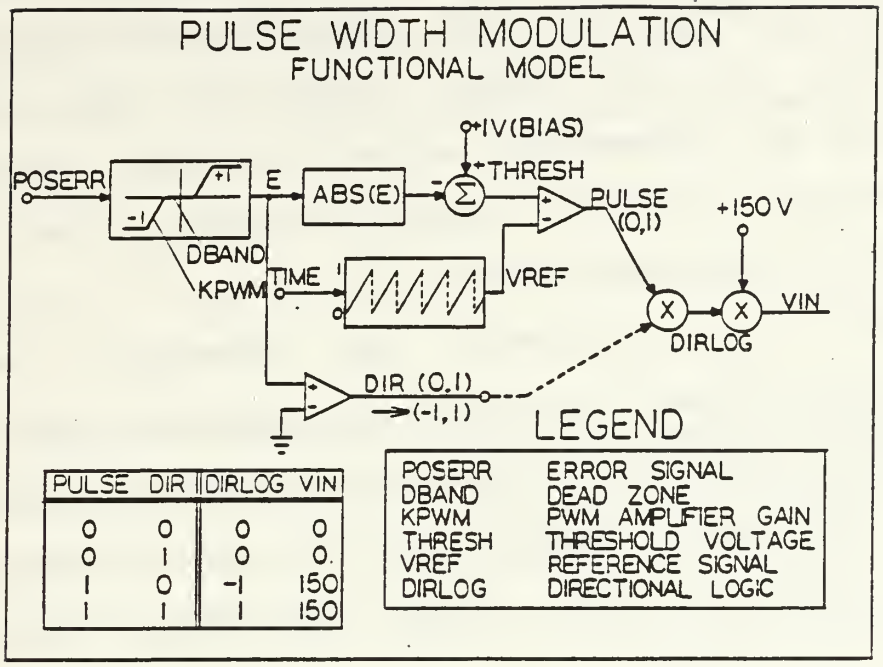
Two distinct categories of error signal amplifiers, linear and nonlinear, are available for this application. The difference between the two lies primarily in the manner in which they drive the solid state devices of the power conditioner. Linear servo-amplifiers drive bipolar transistors in their active regions and permit continuous voltage regulation, while nonlinear servo-amplifiers maintain transistor operation in either saturation or cutoff. Pulse width modulation (PWM) is one method of providing nonlinear servo-amplifier control of a brushless dc motor and is the focus of discussion in this chapter.

While linear servo-amplifier circuits are relatively simple and essentially free of electrical noise, they are subject to thermal damage [Ref.8]. The fact that these amplifiers drive bipolar transistors in their linear region explains the substantial amount of power dissipation into heat that takes place in the commutation switching electronics. Space constraints in the cruise missile fin actuator application preclude the use of large heat sinking elements necessary to protect solid state components from thermal damage. Conversely, pulse width modulated amplification is characterized by negligible power dissipation into heat. Although two state transistor operation is thermally advantageous, it is a source of increased electrical noise due to switching. Fortunately, PWM is negligibly influenced by noise since the random variation of amplitude has little effect on the information contained in the pulse width modulated signal. Additionally, the extent of current ripple and subharmonic oscillation due to the periodic output of the pulse width modulator is insignificant [Ref.6]. Since the power transistors are switched on and off at a frequency far exceeding the motor's bandwidth, the majority of the high frequency component of the modulated signal is filtered by the motor.

Pulse width modulation is a technique for regulating the amount of energy supplied to the motor for development of torque. Effective regulation is accomplished by modulating a fixed voltage amplitude on a reference frequency and linearly scaling its pulse duty cycle.

B. DESCRIPTION

The PWM scheme modeled in this study behaves similarly to the Dither Method outlined by Askinas [Ref.6] and is illustrated in Figure 5.1. A reference sawtooth waveform of desired frequency and amplitude is generated through independent circuitry and is differenced with the closed loop system's amplified position error signal.



PULSE	DIR	DIRLOG	VIN
0	0	0	0
0	1	0	0.
1	0	-1	150
1	1	1	150

POSERR	ERROR SIGNAL
DBAND	DEAD ZONE
KPWM	PWM AMPLIFIER GAIN
THRESH	THRESHOLD VOLTAGE
VREF	REFERENCE SIGNAL
DIRLOG	DIRECTIONAL LOGIC

Figure 5.1 Pulse Width Modulation Functional Model

The amplifier is comprised of linear and nonlinear regions of operation. Nonlinear gain, denoted as "K_{PWM}" in the computer simulations appended, is applied as saturation amplification to the error signal. Relay elements are used to convert the bias of the summed signal to a tri-state logic output which is summarized in Figure 5.1. Because the polarity of the source voltage is fixed, directional rotation is accomplished using separate commutation sequences as shown in Table I. "DIR" is the variable used to indicate commutation direction in the simulation and is assigned a value of +1 for clockwise rotation and -1 for counterclockwise rotation. With "DIR" accounting for directional convention, forcing potential (VIN) is controlled by two-state logic. When PWM logic triggers the application of 150V supply voltage to the motor and determines the commutation sequencing logic requested by the controller, powering conditions remain fixed for the remainder of the reference period.

Figure 5.2 illustrates the convenient one-to-one relationship between the nonlinearly amplified error signal (|E|) and the duty cycle of the pulsed output (PULSE). Due to the saturation amplification of the system error (POSERR), |E| is bounded within the range from zero to unity.

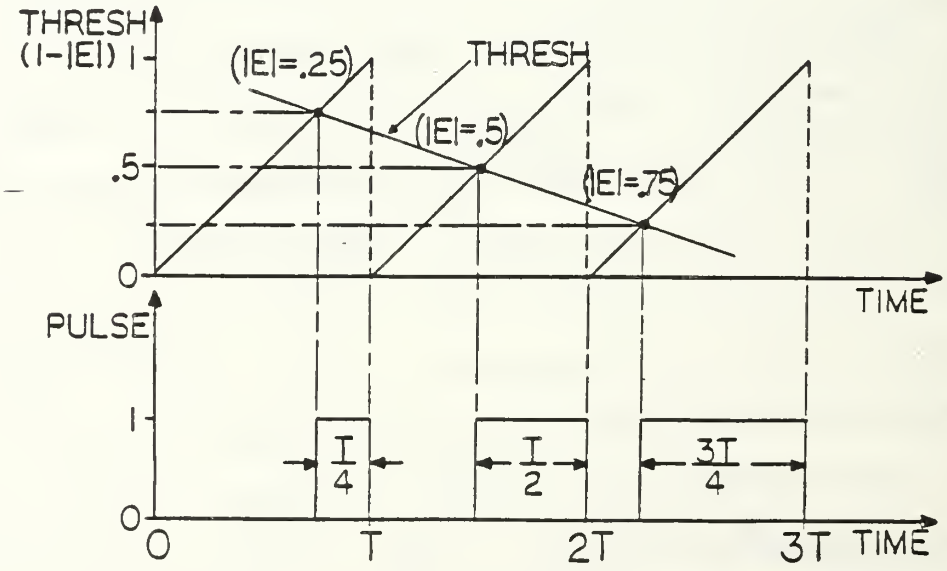


Figure 5.2 Relationship Between |E| and Pulse Duty Cycle

THRESH describes the biased error, and is given by Equation 5.1. When THRESH is less than the reference sawtooth signal during each cycle, VIN is pulsed on by the PULSE signal.

$$\text{THRESH} = 1 - |E| \tag{5.1}$$

The linear nature of the reference sawtooth signal over each pulsing period results in linear scaling of pulse duty cycles when the error is in the range $\{ 0 < |E| < 1 \}$. The relationship observed in Figures 5.1 and 5.2 between E and the duty cycle of VIN is given by Equation 5.2.

$$\text{Duty Cycle of VIN} = |E|*T \tag{5.2}$$

Figures 5.3 through 5.8 are examples of open loop transfer characteristics of the pulse width modulator modeled in this study. Pulse width modulation of ramp and sinusoidal (undamped and exponentially decaying) error signals are examined with varying amplifier gain and dead zone to illustrate its properties. Open loop PWM transfer characteristics are ascertained using the simulation listed in Appendix B. Figure 5.3 depicts the linear scaling range of the PWM amplifier for a specific gain. In this case, K_{PWM} (gain) equals 0.5 and, when applied to the continuous input ramp error signal, results in an increased range of modulation for the directional logic signal. Figure 5.4 illustrates the effect of increased amplifier gain as well as the inclusion of a controller dead zone. For an identical ramp error signal input, the increased gain results in a reduced linear region of modulation. Dead zone is observed in Figure 5.4 near the zero-crossing of the input error signal (t=2.5msec) and is characterized by a corresponding Directional Logic level of 0. Therefore, the use of dead zone in the PWM amplifier buffers the effects of switching when the error signal changes polarity. Figure 5.5 illustrates the pulse width modulation of an undamped sinusoidal error signal with low amplifier gain and no dead zone. The sinusoidal waveform is reasonably well preserved, but would be much improved with a higher sampling frequency. Modulation of the same sinusoid at a higher gain and with dead zone is shown in Figure 5.6. Very little width modulation takes place when gain is high due to saturation effects and causes VIN to resemble the output characteristics of a relay with dead zone. The pulse width modulation of relatively large scale sinusoidal error inputs is examined in Figures 5.5 and 5.6. In position control application, however, error amplitudes associated with stable systems tend to decrease with time. Additionally, larger amplifier gains for this Type 1 system provide improved steady state accuracy and is further discussed in Chapter VI. The exponentially decaying sinusoid used as an input error signal in Figures 5.7 and 5.8 presents a more realistic representation of the range of inputs to be encountered. The low gain configuration illustrated in Figure 5.7 results in linear modulation of the waveform over the range examined and is characterized by the Directional Logic signal pulse width being proportional to the input error signal amplitude. The pulse width characteristically decreases with the exponentrially decaying magnitude of the input. Conversely, the modulation using high gain with the same input is shown in Figure 5.8 and results in saturation of the output pulse as shown by fixed pulse width during periods of relatively large input magnitude.

C. PARAMETER SELECTION

Time averaging provided by low pass characteristics of the brushless dc motor smooth the effects of the discontinuous pulse width modulated forcing function. The PWM may be analytically treated as a piecewise continuous function if specific approximation criteria are satisfied. Validity of such an approximation is principally determined by the reference sawtooth frequency of the PWM. Lumped parameter analysis of this typical motor used in this study reveals an average mechanical time constant, τ_M, of 0.1

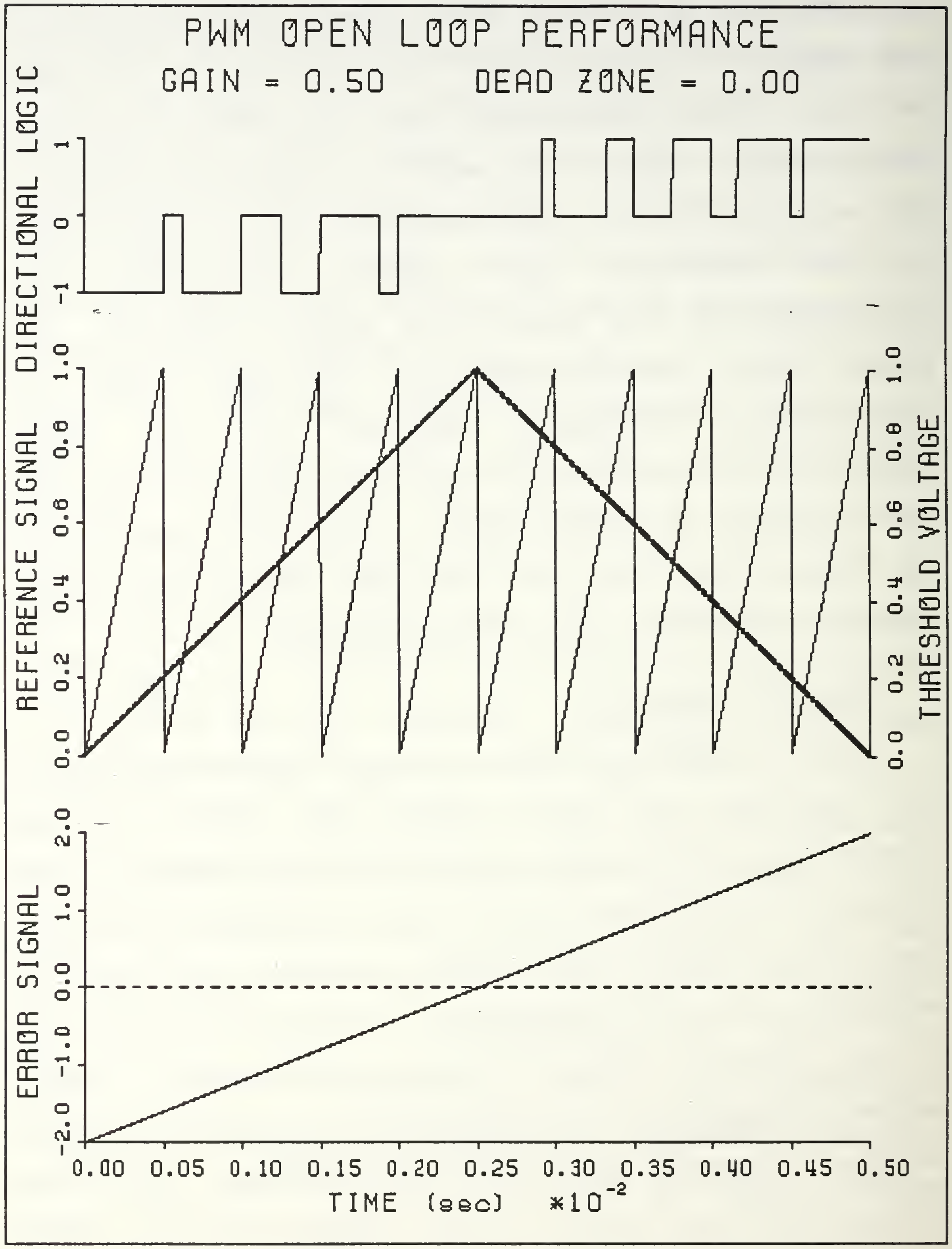


Figure 5.3 PWM Open Loop Transfer Characteristics
(Linear Input, Low Gain, No Dead Zone)

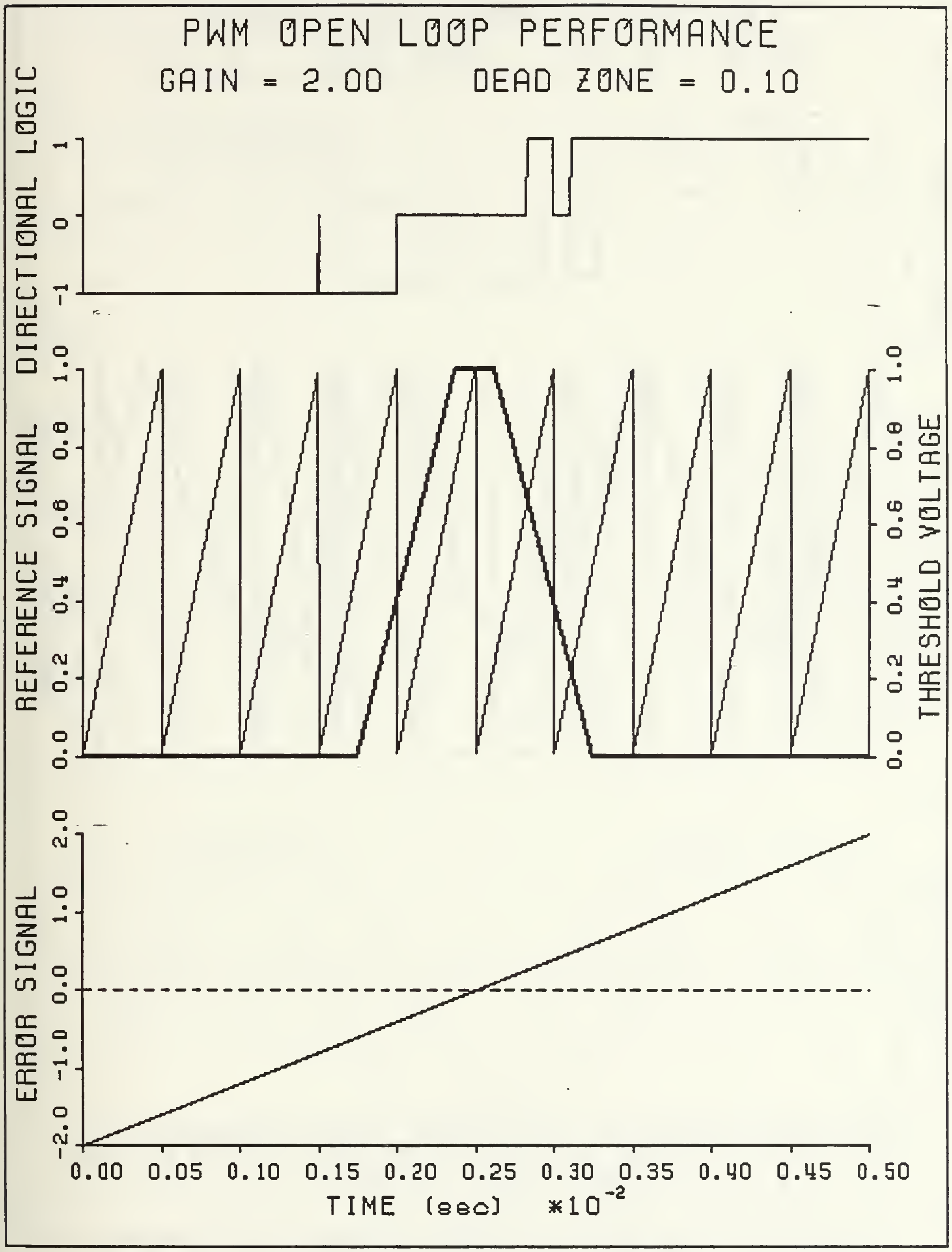


Figure 5.4 PWM Open Loop Transfer Characteristics (Linear Input, High Gain, .1° Dead Zone)

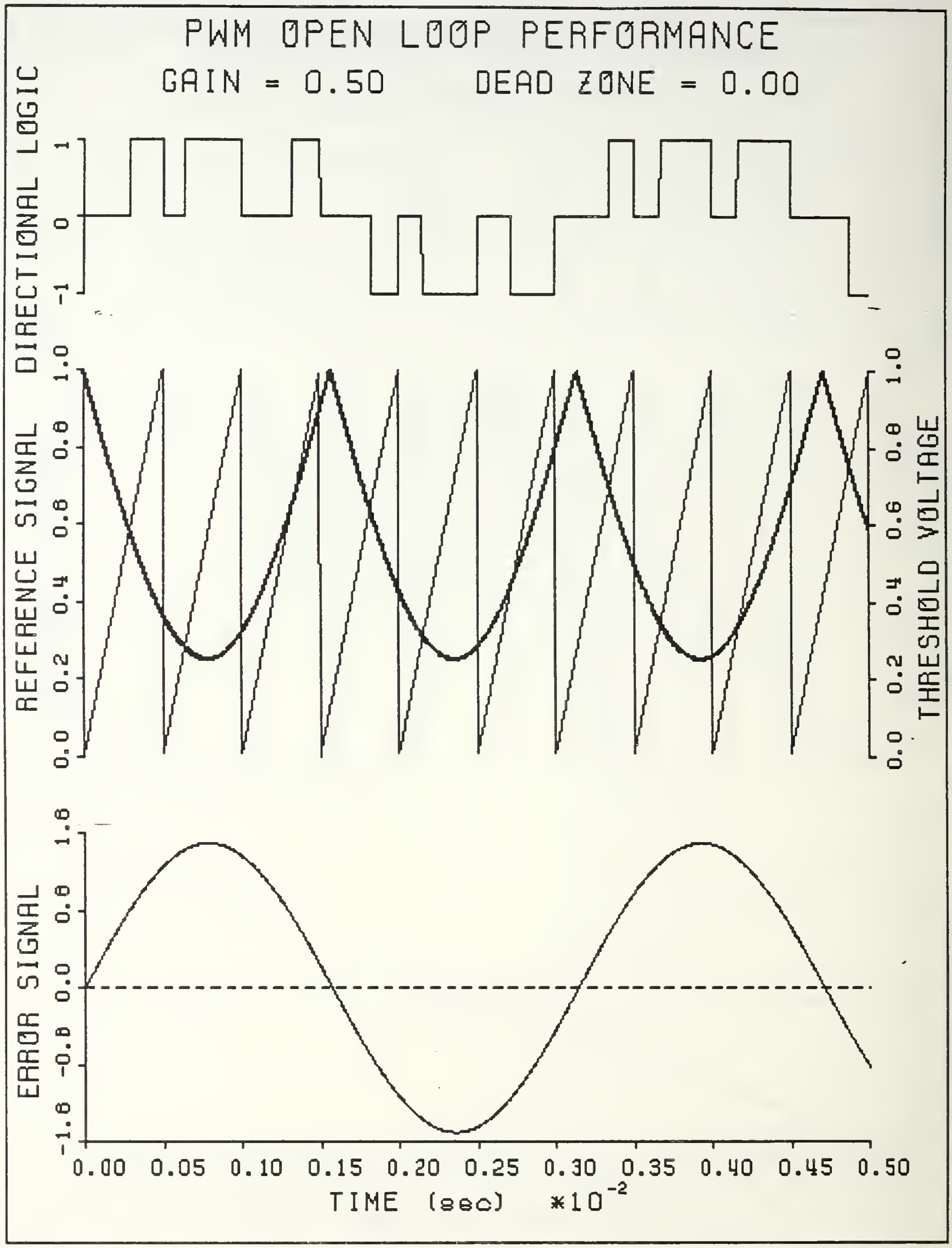


Figure 5.5 PWM Open Loop Transfer Characteristics
(Sinusoidal Input, Low Gain, No Dead Zone)

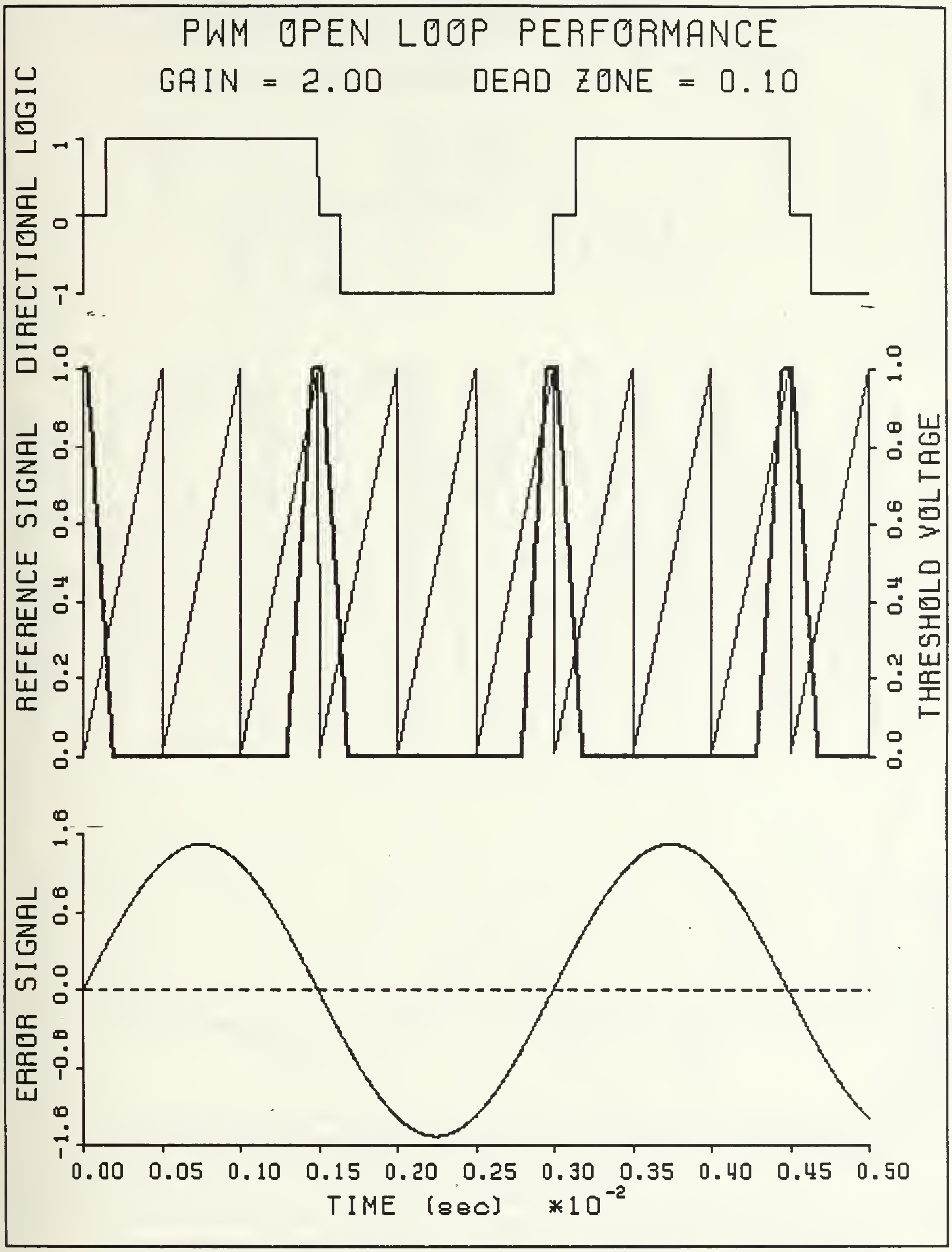


Figure 5.6 PWM Open Loop Transfer Characteristics (Sinusoidal Input, High Gain, .1° Dead Zone)

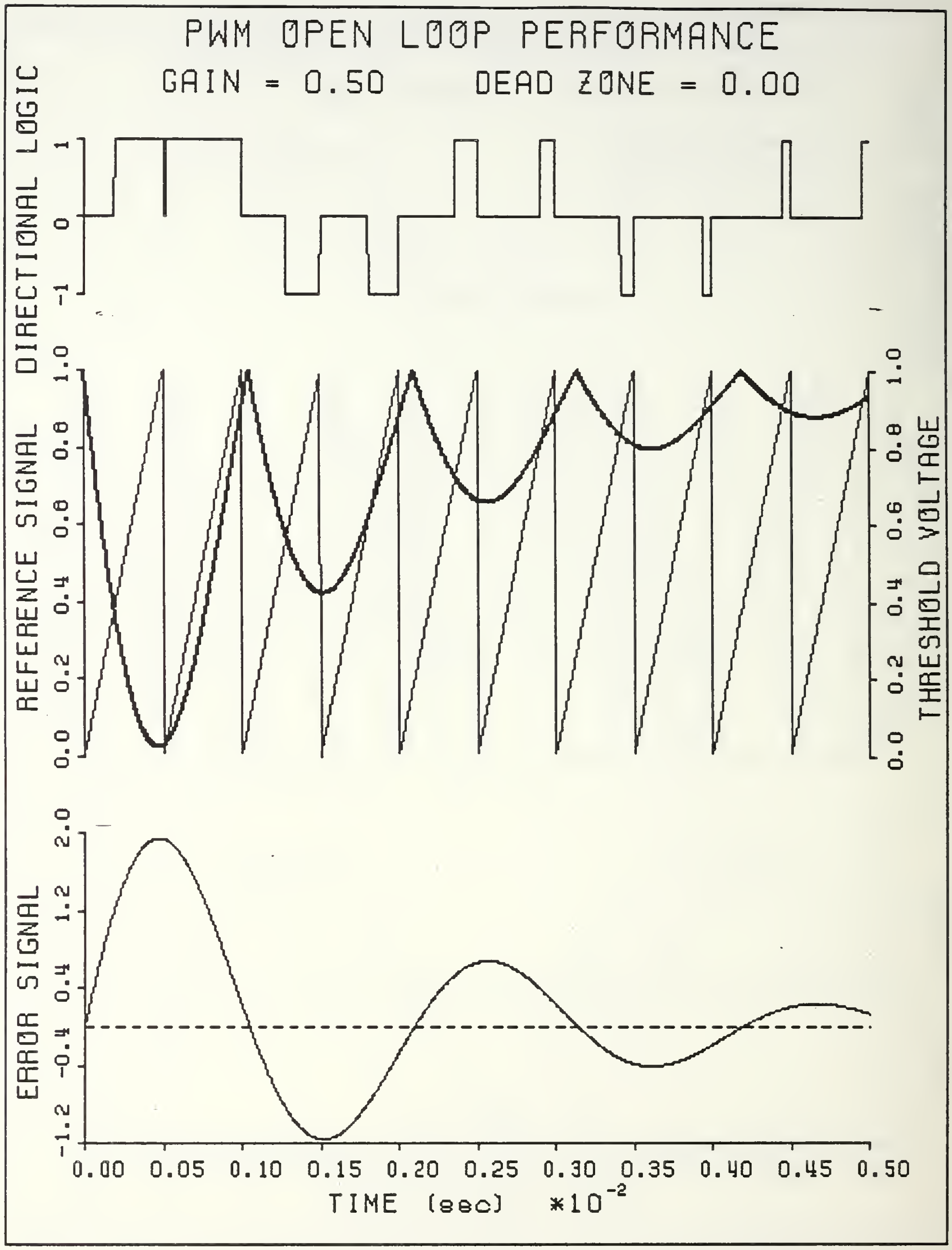


Figure 5.7 PWM Open Loop Transfer Characteristics (Damped Sinusoidal Input, Low Gain, No Dead Zone)

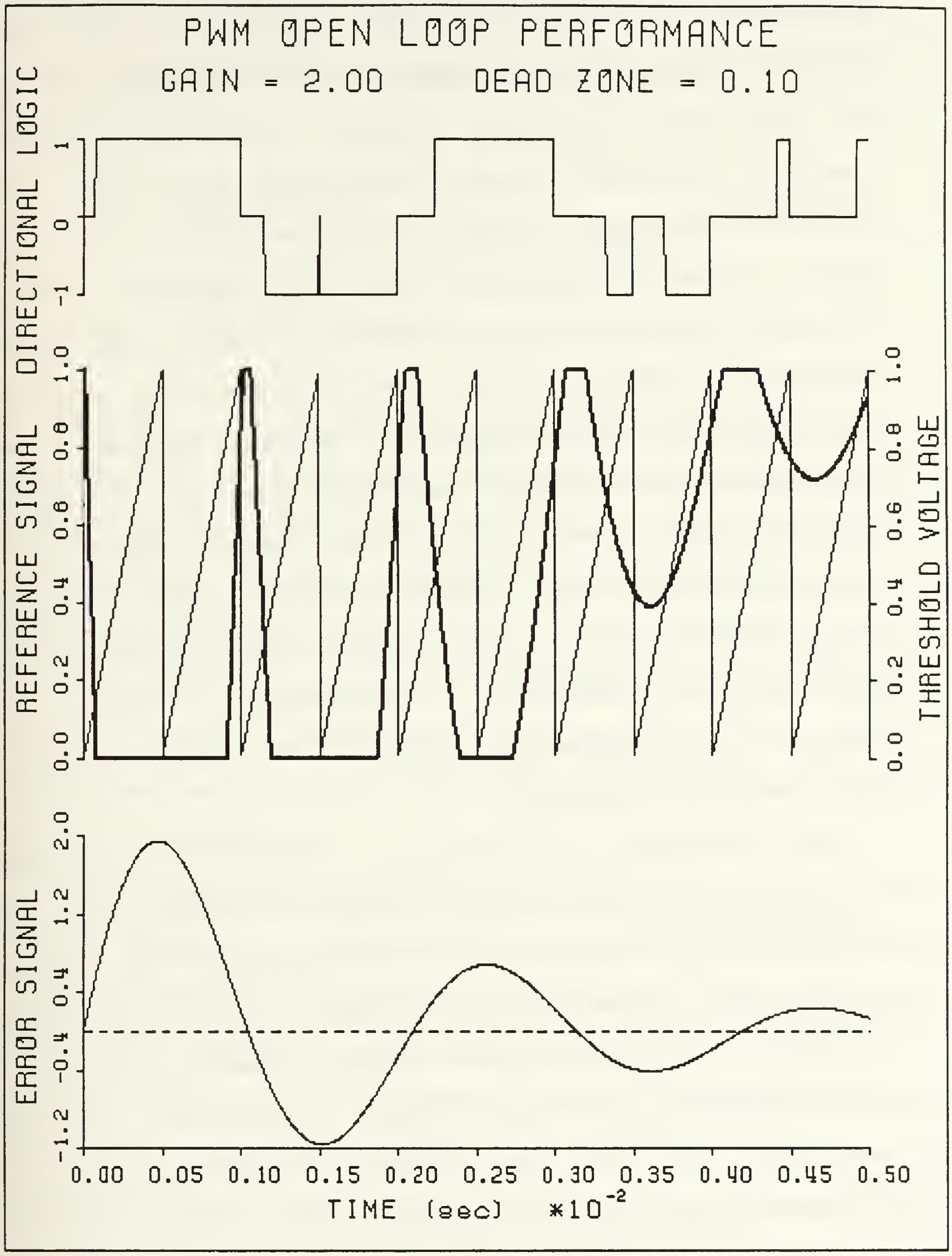


Figure 5.8 PWM Open Loop Transfer Characteristics
(Damped Sinusoidal Input, High Gain, .1° Dead Zone)

seconds and an electrical time constant, τ_E, of .000165 seconds. Despite the dominant low pass characteristics of the slow mechanical time constant, empirical derivation based on computed results indicates the pulse width modulation reference sawtooth frequency should be at least 10KHz. At such frequencies, the motor effectively smoothes the pulsed forcing action of the PWM. Phase plane methods discussed in Chapter VI are used to graphically illustrate the effects of pulse frequency on system response. System simulations using lower sawtooth waveform frequencies indicate stable but very oscillatory response behavior. It is recognized that solid state power switching characteristics pose a limitation on the maximum realizable PWM reference frequency. Therefore, a 10KHz pulse frequency is selected on the basis of response smoothing and hardware constraints.

The selection of simulation step size is largely dependent upon the reference sawtooth waveform frequency. The Nyquist rate determines the minimum sampling frequency required to reconstruct the assumed bandlimited sawtooth waveform. If the step size is chosen less than one-half of the reciprocal of the highest significant frequency component (f_c) of the sawtooth waveform's Fourier transform, then aliasing will be avoided [Ref.10].

Equations 5.3 and 5.4 determine the Nyquist sampling period (T_S) of a periodic sawtooth waveform of period T_P and amplitude E_M.

$$H(f) = \int_0^{T_P} \frac{E_M}{T_P} te^{-j2\pi ft}\, dt \qquad (5.3)$$

$$T_S = 1/(2f_C) = 50\ \mu\text{sec} \qquad (5.4)$$

However, simulation based on the Nyquist rate is observed to be inadequate and does not provide accurate pulse width modulation of error signals. The full range of the sawtooth response $\{0 \le VREF \le 1\}$ must be reconstructed in the simulation to support modulation of small amplitude error signals. Observation of computed results indicates that a minimum simulation step size of an order of magnitude less than the PWM pulse period is required for accurate simulation.

PWM amplifier gain determines the region of pseudo linear operation. Consequently, large gains result in hard response characteristics near steady state, while low gains allow soft behavior. The interaction of PWM frequency and gain may result in unacceptable residual oscillations and ballistic overshoot conditions. This self excited oscillation, or limit cycle, is commonly associated with nonlinear servo-amplifier control and will be studied more completely in Chapter VI using phase plane methods.

VI. PRELIMINARY PHASE PLANE DESIGN

A. BACKGROUND

The highly nonlinear and discontinuous nature of a pulse width modulated position controller precludes the use of most classical stability analysis methods. Computer simulation lends itself well to simple time response analysis, but restriction to such a method often masks many of the underlying characteristics which determine a system's general behavior. Nonlinear controllers are most often analyzed with either describing function or phase plane techniques. The describing function is a frequency response method which ultimately determines transfer function characteristics of the control system. However, the discontinuous nature of pulse width modulation limits the effectiveness of the describing function. Phase plane methods, on the other hand, are well suited to handle the PWM stability problem provided that a second order model is applicable and the methods are complemented by numerical simulation of the time response of state trajectories.

The underlying premise of analyzing a second order system in the phase plane is that linear and nonlinear components of its characteristic differential equation can be partitioned. Consider the general form of a second order differential equation describing the response of e(t) and given by Equation 6.1.

$$\ddot{e} + f(e,\dot{e}) = 0 \qquad (6.1)$$

The term $f(e,\dot{e})$ is a nonlinear function of e(t) and $\dot{e}(t)$ when equation 6.1 describes the fin actuator's performance. Rather than studying e(t) and $\dot{e}(t)$ parametrically, the composite function $\dot{e}(e(t))$ can be determined and studied graphically. The phase plane portrait of $\dot{e}(t)$ versus e(t) bears a wealth of information describing a system's dynamics which is otherwise lost in parametric analysis of the time solutions.

The intent of this chapter is to develop the phase plane method of analysis as a primary tool for studying the dynamics associated with position control of brushless dc motors. Additionally, preliminary values for design parameters will be determined based on system performance criteria.

B. LINEAR APPROXIMATION

State space methods associated with phase plane portrait development are not well suited for analysis of the detailed brushless dc motor model. Such an approach involves the use of a third order model with very stiff dynamics and would be computationally cumbersome and inefficient. However, the detailed model may be approximated by the linear lumped parameter third order model shown in Figure 6.1. Average system parameters for the typical motor used in this study are given in Table II.

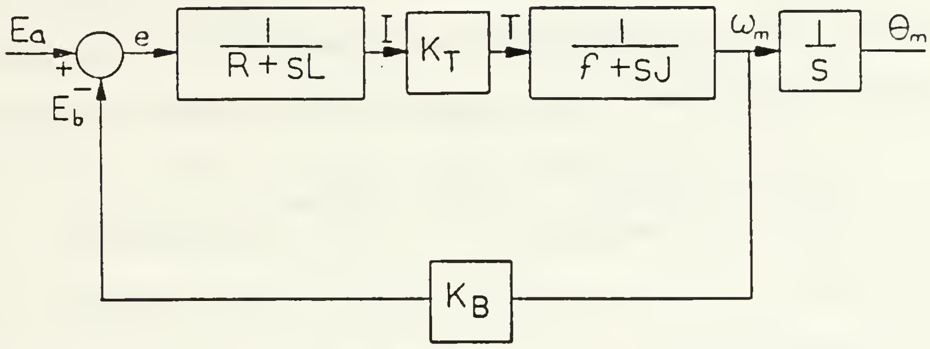


Figure 6.1 Third Order Lumped Parameter Model

TABLE II

AVERAGE SYSTEM PARAMETERS

Viscous Friction	f	.01	[oz-in/sec]
Motor Inertia	J	.001	[oz-in/sec^2]
Equiv Resistance	R	9.7	[ohms]
Equiv Inductance	L	.0016	[henries]
Torque Constant	K_T	15.9	[oz-in/amp]
Back EMF Constant	K_B	.112	[volts/rad/sec]

The lumped parameter model's validity as an acceptable representation of the 3-phase, 4-pole brushless dc motor may be demonstrated using analytic and computer simulation methods. The closed loop transfer function describing the block structure of Figure 6.1 for $\Omega(s)/E_a(s)$ is given by Equation 6.2.

$$\frac{\Omega(s)}{E_a(s)} = \frac{K_T}{(R + sL)\ (f + sJ) + K_T K_B} \qquad (6.2)$$

For a step input magnitude of $E_a = 150$v, steady state output can be obtained using the final value theorem. The steady state velocity (ω_{ss}) is determined in Equation 6.3.

$$\omega_{ss} = \frac{E_a\ K_T}{fR + K_T K_B} = 1270 \text{ rad/sec} \qquad (6.3)$$

Assuming a 10:1 mechanical transmission speed reduction, velocity may be converted from rad/sec to fin-deg/sec.

$$\omega_{fss} = (1270\ \frac{\text{rad}}{\text{sec}})(57.3\ \frac{\text{deg}}{\text{rad}})(0.1) = 7277\ \frac{\text{fin-deg}}{\text{sec}}$$

Motor current is also of interest in the verification of the averaged parameter model and the transfer function $I(s)/E_a(s)$ is given by Equation 6.4.

$$\frac{I(s)}{E_a(s)} = \frac{f + sJ}{(R+sL)\ (f+sJ) + K_T K_B} \qquad (6.4)$$

Again, using a step input of magnitude $E_a = 150v$, steady state current is obtained using the final value theorem and is calculated in Equation 6.5.

$$I_{ss} = \frac{E_a f}{fR + K_T K_B} = 0.79 \text{ amps} \qquad (6.5)$$

Velocity and current response characteristics of both the third order lumped parameter model and the detailed brushless dc motor model are simulated using programs listed in Appendices A and C, respectively, and the results for fin velocity and current response are illustrated in Figures 6.2 through 6.5. Simulated response characteristics support analytically determined steady state behavior of the third order lumped parameter model. The ripple component in the motor current caused by back emf generation in the brushless dc motor constitutes the principal difference in performance between the two models. General performance similitude indicates the brushless dc motor may be accurately represented with respect to its mechanical and electrical response using an averaged parameter model.

Although phase space methods support solution of third order systems, the extra simulation time and programming effort involved do not justify inclusion of a third dimension in the portrait of this system. The electrical

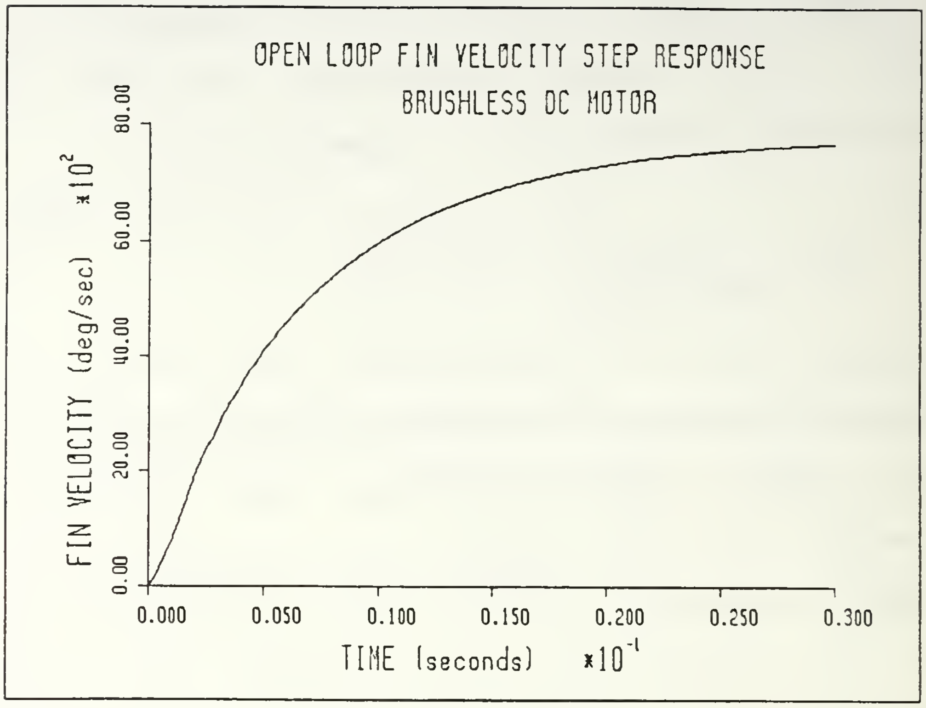


Figure 6.2 Brushless DC Motor Fin Velocity Step Response

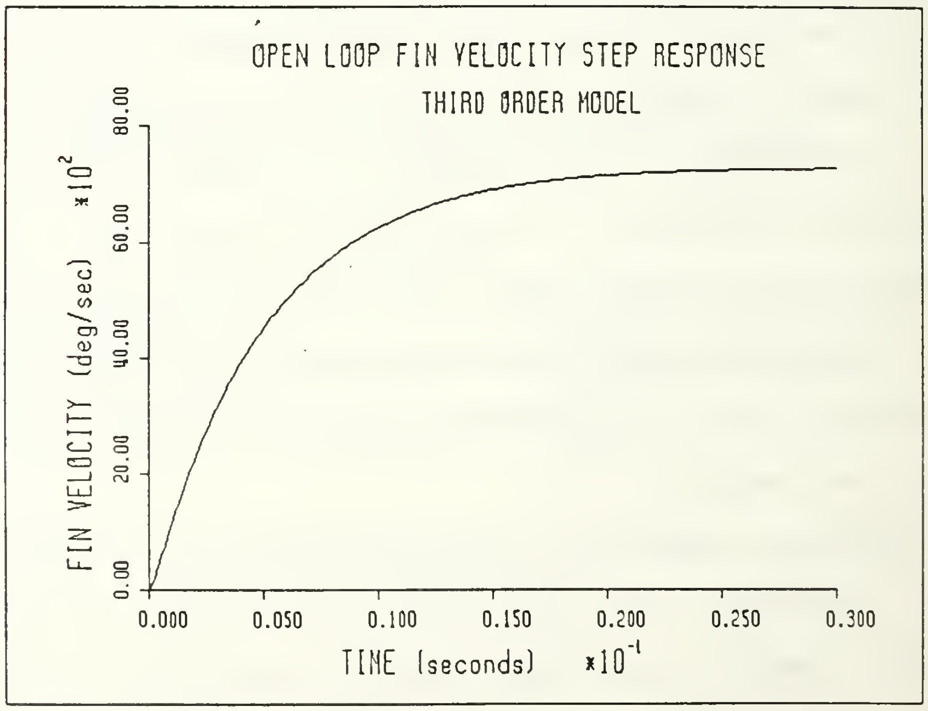


Figure 6.3 Third Order Model Fin Velocity Step Response

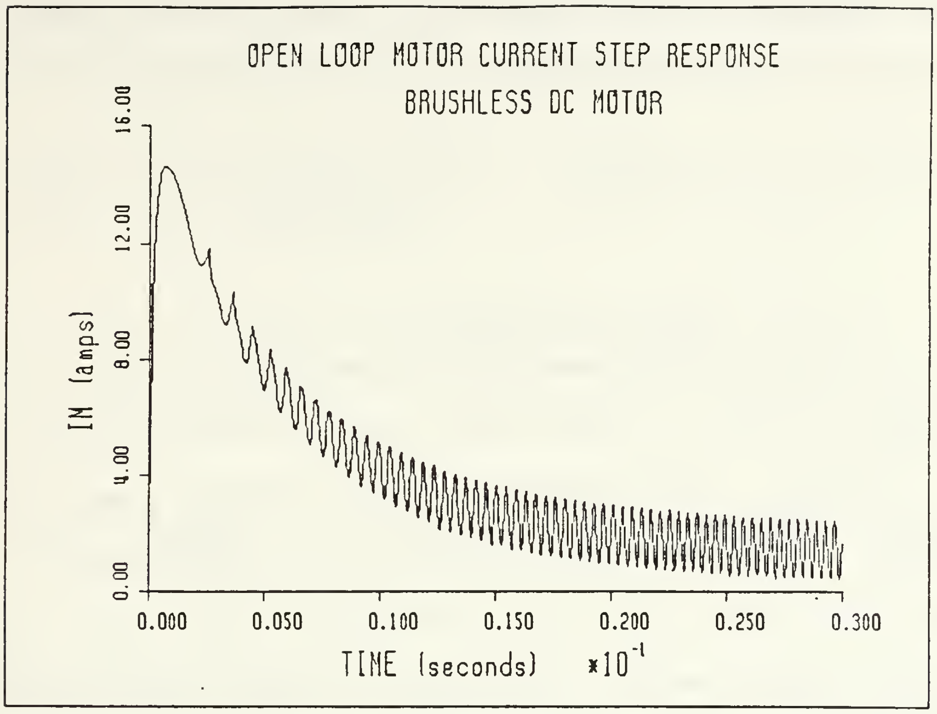


Figure 6.4 Brushless DC Motor Current Step Response

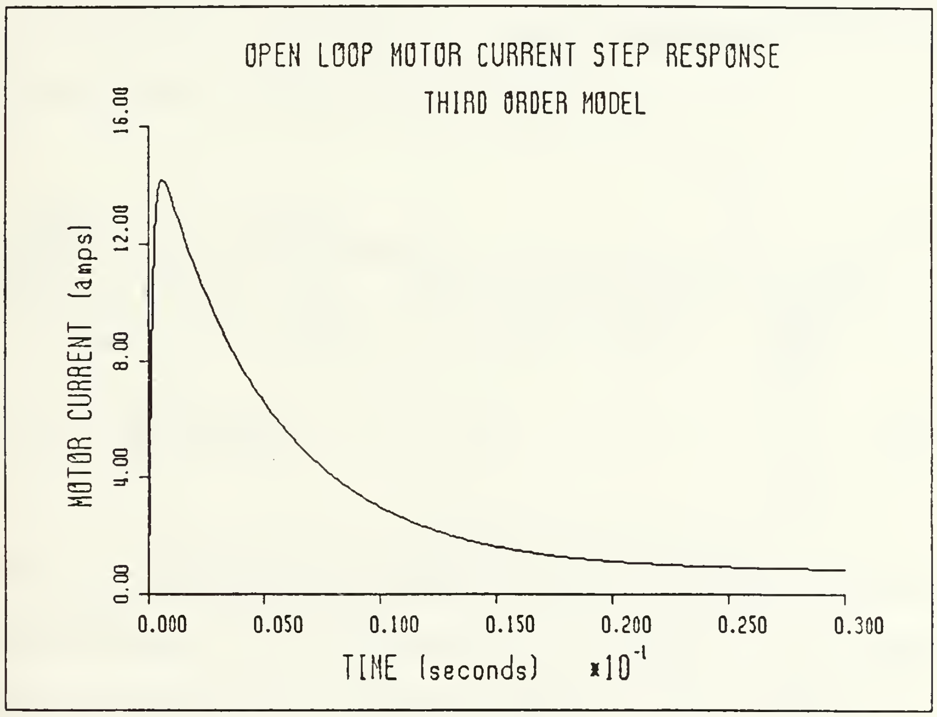


Figure 6.5 Third Order Model Motor Current Step Response

and mechanical time constants of the motor are determined by Equations 6.6 and 6.7.

$$\tau_E = \frac{L}{R} = \frac{.0016\ h}{9.7\Omega} = .000165\ \text{sec} \tag{6.6}$$

$$\tau_M = \frac{J}{f} = \frac{.001\ (\text{oz-in/s}^2)}{.01\ (\text{oz-in/s})} = 0.1\ \text{sec} \tag{6.7}$$

Clearly, the mechanical time constant dominates general system response and results in low pass behavior. Neglecting the fast time constant, that is, assuming no circuit inductance, the system performance should remain virtually unchanged. This reduced order model is shown in Figure 6.6 and can be verified as a legitimate substitute for the third order model.

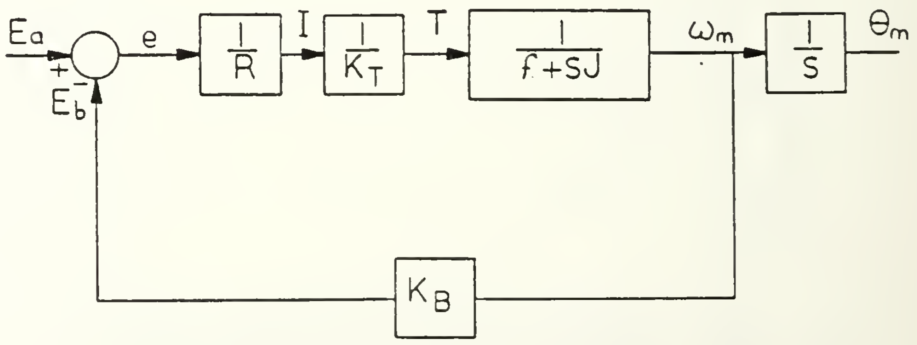


Figure 6.6 Reduced Order Lumped Parameter Model

Equation 6.8 gives the closed loop transfer function relationship describing the reduced order model.

$$\frac{\Omega(s)}{E_a(s)} = \frac{K_T/JR}{s + \frac{fR + K_T K_B}{JR}} \qquad (6.8)$$

The final value theorem is used to determine the steady state velocity when a step amplitude E_a = 150v is applied.

$$\omega_{ss} = \frac{K_T E_a}{fR+K_T K_B} = 1270 \frac{\text{rad}}{\text{sec}} \rightarrow \omega_{ss}=7277 \frac{\text{fin-deg}}{\text{sec}} \qquad (6.9)$$

The motor current response start-up performance is significantly affected by the removal of circuit inductance and its associated lag, but retains similar steady state characteristics as determined by Equations 6.10 and 6.11 and illustrated in Figures 6.7 and 6.8.

$$\frac{I(s)}{E_a(s)} = \frac{f + sJ}{R\ (f+sJ) + K_T K_B} \qquad (6.10)$$

$$I_{ss} = \frac{E_a f}{fR + K_T K_B} = 0.79 \text{ amps} \qquad (6.11)$$

Table III summarizes performance characteristics of the detailed model of the brushless dc motor, its third order linear approximation, and the reduced order model.

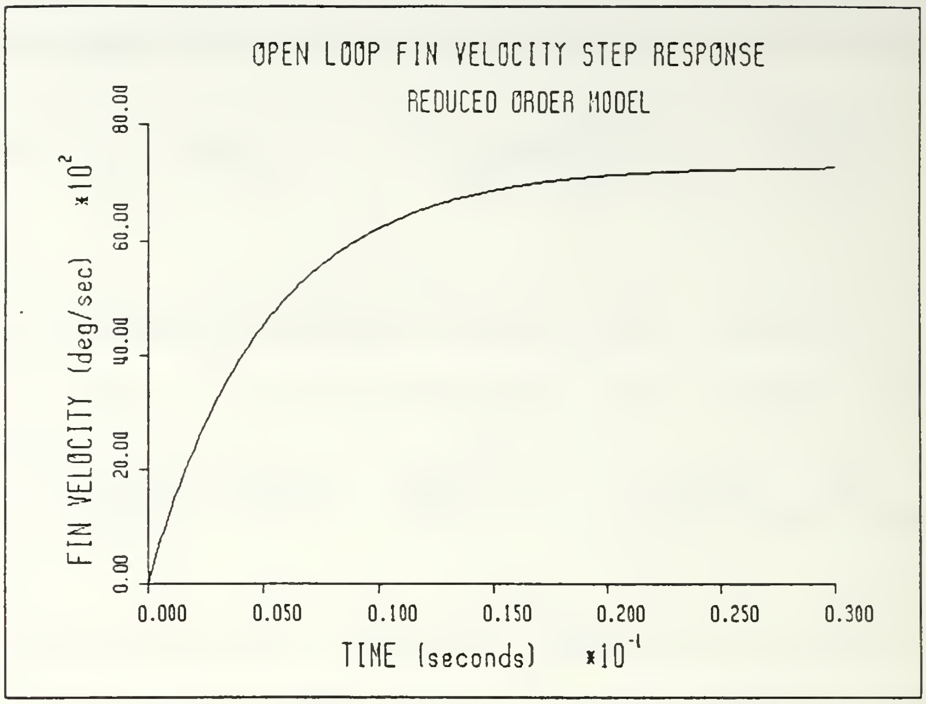


Figure 6.7 Reduced Order Model Fin Velocity Step Response

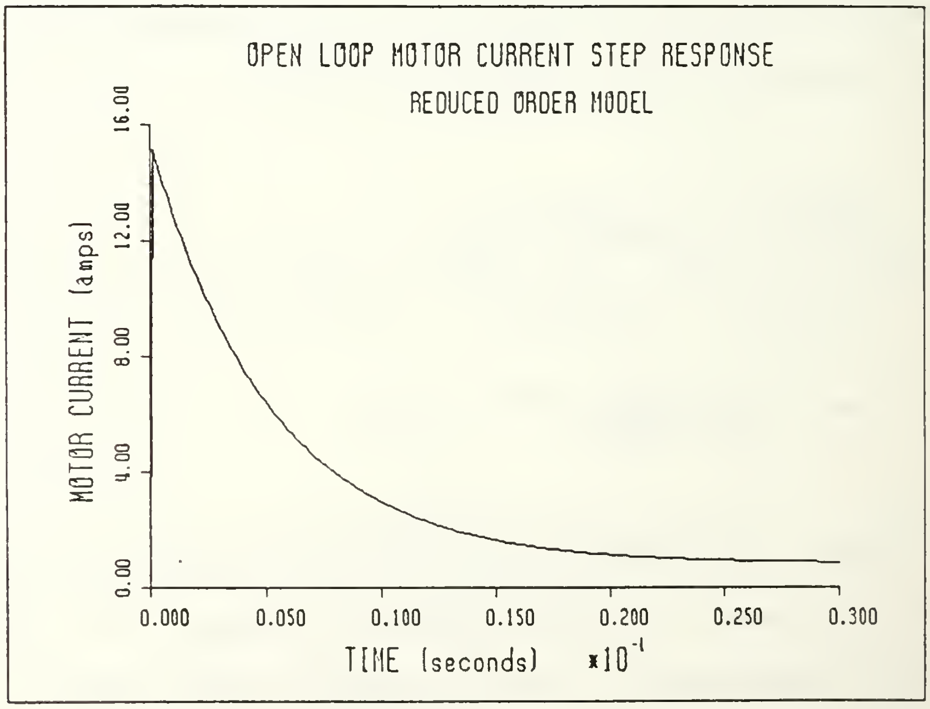


Figure 6.8 Reduced Order Model Motor Current Step Response

Correlation is very strong between the detailed and reduced order models, substantiating its use.

TABLE III

LINEAR APPROXIMATION VALIDATION

	Brushless DC Motor	Third Order Approximation	Reduced Order Approximation
Ω_{ss} [°fin/sec]	7670	7277	7277
I_{ss} [amps]	1.4 (avg)†	0.79	0.79
t_{settle} [sec] (± 2%)	.0275	.0225	.0225
I_{peak} [amps]	14.59	14.20	15.5
t_{rise} [sec] (10%-90%)	.0145	.0118	.0120

C. DEVELOPMENT

The computer aided phase plane program developed for analyzing this system is listed in Appendix D and graphically superpositions the simulated time dependent trajectory and the state space solutions for a sufficiently representative region of values of e and $\dot{e}$. The analytically determined state space solutions are illustrated as slope markers which indicate the instantaneous slopes of $\dot{e}(e(t))$ at any condition $(e,\dot{e})$. If the range of $\dot{e}$ and e to be examined is reasonably

† Steady state conditions not reached at t = 0.3 sec. Extended simulation reveals $I_{ss}(t=0.05 \text{ sec}) \rightarrow 1.1$ amp.

representative of the normal operating conditions of the system, stability may be validated by the exclusion of any singular points, areas of local convergence, or areas of divergence. The criterion for stability in this design is absolute convergence to a stable equilibrium point representing steady state conditions or, as is common in many nonlinear systems, convergence to a limit cycle about steady state.

A limit cycle is an isolated closed path or trajectory in the phase plane and describes a system's self-excited oscillation [Ref.11]. If the limit cycle is unstable, the closed loop path constitutes the boundary between stable and unstable regions. For a stable limit cycle, trajectories outside and in the vicinity of a stable limit cycle will converge to it, while those trajectories inside will diverge to the limit cycle. Limit cycle behavior is anticipated in pulse width modulated position control of the brushless dc motor due to inherent time delay in switching and is further investigated in this chapter.

A simulated trajectory represents actual system performance over time when specific initial conditions are imposed. While the trajectory offers tremendous insight into the system's dynamics for specific response conditions, the unique value of phase plane analysis lies in the general state space solution presented in the phase plane portrait. Figure 6.9 illustrates the reduced order model configured for closed loop fin position control. The block structure is expanded to identify necessary states of the second order system.

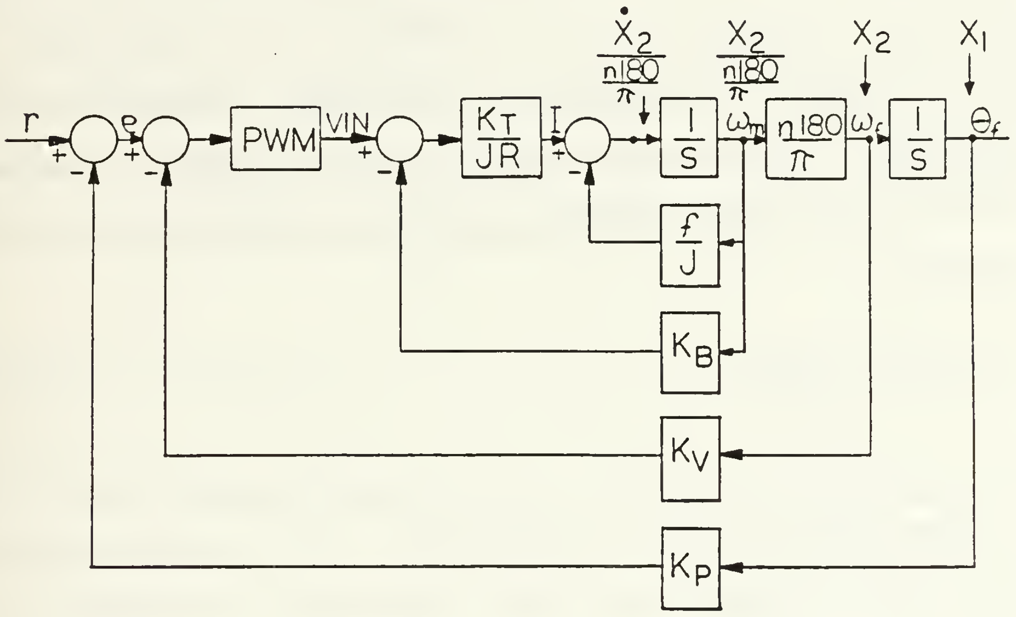


Figure 6.9 Closed Loop Reduced Order Model State Diagram

The system's state equations are developed for the purpose of defining instantaneous slope vectors (η) as functions of error (e) and error rate ($\dot{e}$).

$$\eta = f(e,\dot{e}) = \frac{d\ \dot{e}(t)}{d\ e(t)} \tag{6.12}$$

Fin position (θ_{FIN}) in degrees is assigned the state variable x_1. Its derivative state (ω_{FIN}) in fin-deg/sec is x_2.

$$\dot{x}_1 = x_2 \tag{6.13}$$

To describe higher order state variables, it is necessary to introduce and apply a scalar transmission factor ($\Omega°$) which converts units from Motor Radians to Fin Degrees.

$$\Omega° = \frac{n\ 180°}{\pi} \tag{6.14}$$

The variable "n" of Equation 6.14 is the motor to fin mechanical transmission gear ratio and is assumed to be 0.1 in this study. Angular acceleration of the fin in deg/sec^2 is given by Equation 6.15.

$$\dot{x}_2 = \frac{\Omega°\ K_T\ VIN(e,\dot{e})\ -\ (K_T K_B\ +\ fR)\ x_2}{JR} \tag{6.15}$$

Closed loop system error (e) is defined via position and velocity feedback circuits and is given by Equation 6.16. The dynamic nature of the missile guidance and flight control result in the fin controller behaving more as a position tracking vice positioning device. Therefore, while step response analysis is important to determine the general behavior of the motor, it is solely inadequate to characterize the overall behavior of the system. Ramp response analysis more completely describes the motor's dynamic positioning performance. Using the phase plane simulation developed for this study, a ramp input whose time dependence is scaled by its slope ($\dot{r}$) is used to evaluate system tracking performance. Step response analysis is performed by describing initial perturbation conditions ($e(0),\dot{e}(0)$) and zeroing the ramp slope.

$$e = \dot{r}\,t - K_p\,x_1 \tag{6.16}$$

Differentiating Equation 6.16 yields the system's error rate, $\dot{e}$.

$$\dot{e} = \dot{r} - K_p\,x_2 \tag{6.17}$$

Manipulation of these equations of state is required to determine expressions for x_2 and $\dot{x}_2$ solely in terms of e and $\dot{e}$. Equations 6.17 may be rewritten as Equation 6.18.

$$x_2 = \frac{\dot{r} - \dot{e}}{K_p} \tag{6.18}$$

Substitution of Equation 6.18 into 6.15 yields Equation 6.19.

$$\dot{x}_2 = \frac{\Omega^\circ K_T K_P \, VIN(e,\dot{e}) - (K_T K_B + fR)(\dot{r} - \dot{e})}{JR \, K_P} \qquad (6.19)$$

Finally, the instantaneous slope function (η) is given by Equation 6.20, and is composed of natural and forced components.

$$\eta = f(e,\dot{e}) = \frac{d \, \dot{e}(t)}{d \, e(t)} = - \frac{K_P \, \dot{x}_2}{\dot{r} - K_P x_2} = - K_P \, \dot{x}_2 / \dot{e}$$

$$\eta = \frac{-\Omega^\circ K_T K_P \, VIN(e,\dot{e}) + (\dot{e} - \dot{r})(K_T K_B + fR)}{JR \, \dot{e}} \qquad (6.20)$$

The slope function (η) is linear in terms of e and ė, except for the VIN(e,ė) term. The nonlinearity arises from transfer function characteristics of the pulse width modulator. Because of the distinct segregation of linear and nonlinear elements, however, the model may be approximated as a piecewise linear system. The phase plane is subdivided into several regions whose commonalty is local linear operation. These regions are graphically bounded by lines of discontinuity on the phase plane portrait. Table IV describes the five piecewise continuous regions of operation associated with saturation amplifier and PWM servo control. The use of relay control involves regions 1, 4, and 5 only.

TABLE IV

PIECEWISE CONTINUOUS APPROXIMATION

Region#	Error Condition	VIN(e,ė)	Slope
1 (Dead Zone)	$\lvert P_1 \rvert \leq DBAND$	0	$\frac{(K_T K_B + fR)(\dot{r} - \dot{e})}{JR\dot{e}}$
	...where	$P_1 = e + \frac{\dot{e} K_V}{K_P} + e_{ss}$	
2 (Positive Linear)	$0 < P_2 < 1$	$150P_2$	$-\left\{ \frac{(150P)\Omega^\circ K_T K_P + (\dot{r} - \dot{e})(K_T K_B + fR)}{JR\dot{e}} \right\}$
	...where	$P_2 = K_{PWM}(e + \frac{\dot{e} K_V}{K_P} - DBAND - e_{ss})$	
3 (Negative Linear)	$-1 < P_3 < 0$	$150P_3$	$-\left\{ \frac{(150P)\Omega^\circ K_T K_P + (\dot{r} - \dot{e})(K_T K_B + fR)}{JR\dot{e}} \right\}$
	...where	$P_3 = K_{PWM}(e + \frac{\dot{e} K_V}{K_P} + DBAND - e_{ss})$	
4 (Positive Saturation)	$P_4 \geq 1$	$150P_4$	$-\left\{ \frac{(150)\Omega^\circ K_T K_P + (\dot{r} - \dot{e})(K_T K_B + fR)}{JR\dot{e}} \right\}$
	...where	$P_4 = K_{PWM}(e + \frac{\dot{e} K_V}{K_P} - DBAND - e_{ss})$	
5 (Negative Saturation)	$P_5 \leq -1$	$150P_5$	$-\left\{ \frac{(150)\Omega^\circ K_T K_P + (\dot{r} - \dot{e})(K_T K_B + fR)}{JR\dot{e}} \right\}$
	...where	$P_5 = K_{PWM}(e + \frac{\dot{e} K_V}{K_P} + DBAND - e_{ss})$	

Excluding dead zone error, the steady state error, e_{ss}, of this Type 1 system is of finite value for ramp response and zero when stepped. e_{ss} is determined by Equation 6.21 and permits correct ramp response prediction using state space solution techniques.

$$K_V = \lim_{s\to 0} \frac{s\,[\,\dot{r}(s)\,]}{1+G(s)H(s)}$$

$$e_{ss} = \frac{\dot{r}}{K_V} = \frac{\dot{r}(fR+K_T K_B)}{\Omega^\circ K_T K_P K_A VIN} + \frac{\dot{r}\,K_V}{K_P} + \text{Dead Zone} \qquad (6.21)$$

K_a is the amplifier gain associated with the nonlinear controller. K_{PWM}, as defined in Chapter V, is substituted for K_a when pulse width modulation is employed.

Interpretation of Equation 6.21 describes the effects of amplifier gain on e_{ss}. If K_a is infinitely large, such as in the case of an ideal relay, the steady state error is minimized and is approximated by Equation 6.22.

$$e_{ss}(\text{relay}) = \frac{\dot{r}\,K_V}{K_P} + \text{Dead Zone} \qquad (6.22)$$

However, as K_a is reduced, the first term of Equation 6.21 bears more significance and the steady state error is increased. Thus, system accuracy is readily ascertained using analytical methods and is presented for comparison with the simulated trajectory as an asterisk ("*") on the phase plane portrait.

As discussed previously, the output of the PWM is either 0 or 150v. However, the pulse duration is a nonlinear function of error. Since the pulse width modulator is described in terms of e and $\dot{e}$, as well as by time, difficulty exists in trying to illustrate three dimensional characteristics on a two dimensional phase plane. However, the nonlinear dependency on time may be alleviated through linear approximation methods. This is accomplished by time averaging the response of the PWM. The result of such a linearization closely approximates the characteristics of a saturating amplifier. Specifically, the function which describes the average output of these two nonlinear elements is the same. The average dc voltage of the PWM is defined by Equation 6.23.

$$\overline{V_{DC}} = \frac{1}{T}\int_{0}^{T} V_{out}\, dt = \text{Pulse Duty Cycle}*150\text{v} \qquad (6.23)$$

The variable "T" represents the period of the PWM's pulse cycle.

The instantaneous error of the system is nonlinearly scaled by the PWM amplifier gain (K_{PWM}) and was discussed in detail in Chapter V where essentially, error undergoes normalized saturation amplification. The normalized value of amplified error is the same as the pulsed voltage output duty cycle of the PWM.

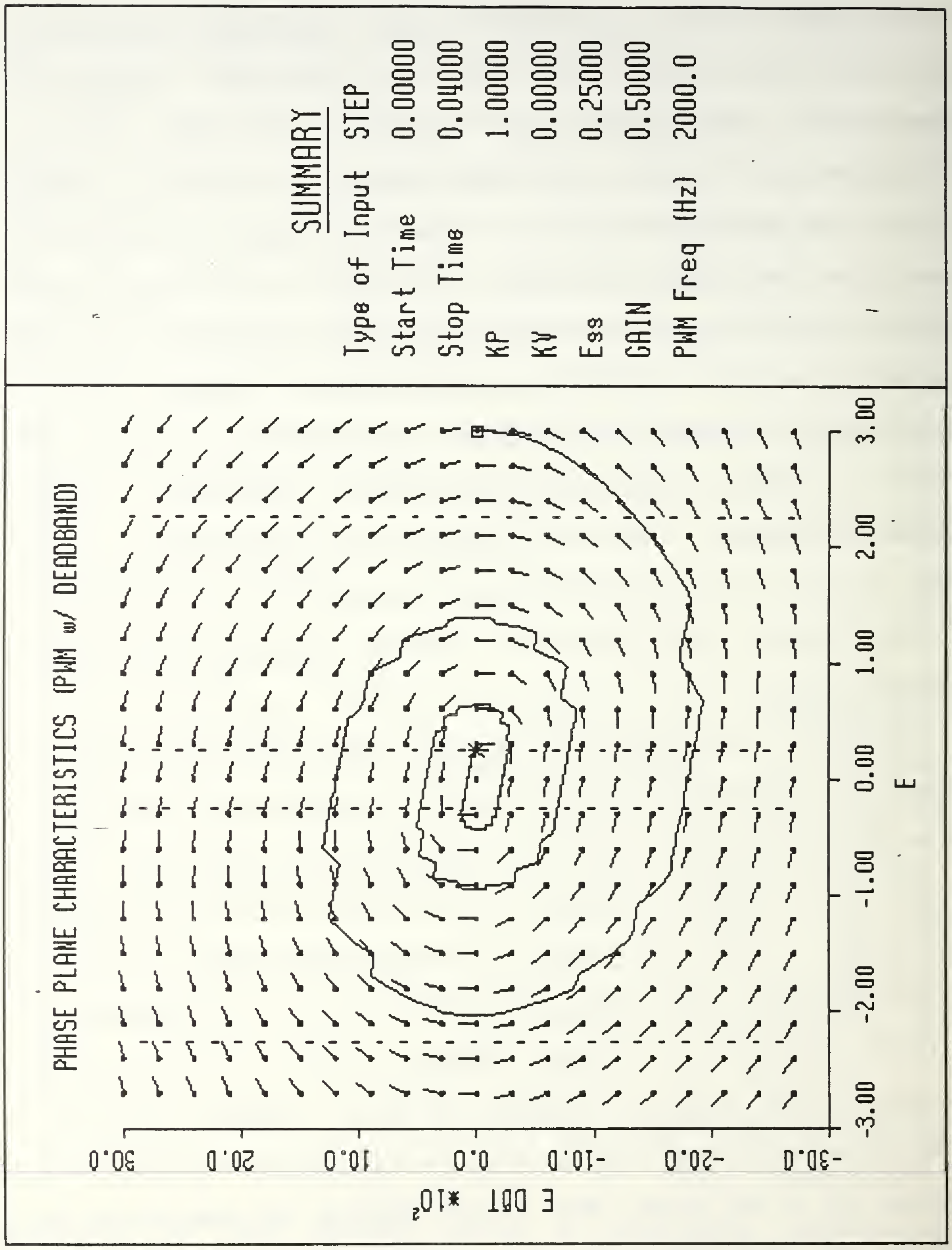
This one-to-one relationship between input error and output voltage circumvents the otherwise required dependency on the time variable to describe pulse duration. The phase plane portrait of a saturating amplifier will be used to predict the simulated trajectory of the pulse width modulated reduced order model. It must be kept in mind, however, that while the piecewise continuous saturating amplifier provides a good average approximation of the PWM's discontinuous characteristics, instantaneous deviations will exist.

D. SYSTEM PERFORMANCE

Four principal design parameters are realistically available for optimizing system performance. The lumped parameters of the reduced order model preclude variation of actual component characteristics of the brushless dc motor. Coefficients for position and velocity feedback (K_p and K_v), pulse width modulation amplifier gain (K_{PWM}), and PWM pulse frequency (f_{PWM}) are considered free parameters in this design and are the focus of study in this section.

Since the pulse width modulator's performance can be most clearly evaluated relative to ideal conditions, analysis of the system using a similarly configured saturating amplifier and ideal relay are initially considered. The continuous time saturating amplifier describes the PWM with very high amplifier gain. Identical simulation conditions are imposed on each system configuration. Small scale step response is attained using an initial perturbation of 3°. The pulse width modulator is configured with intentionally low values of amplifier gain and pulsing frequency to accentuate their effects on system performance. For similar reasons, velocity feedback is not used in this illustrative trial. A relatively large dead zone of ±0.25° is simulated to facilitate observation of the system's natural response. Phase plane characteristics of PWM, relay, and saturating amplifier controlled systems for a step input are shown in Figures 6.10 through 6.12, respectively.

Each of the three controller configurations display identical response characteristics in the dead zone and saturation regions. This is anticipated since, in these regions, all three nonlinear controllers are characterized by either 0 or 150 volts of continuous output. It is interesting to note that the PWM model is unaffected by pulsing frequency in these regions. This is due to the system error being outside of the linear range of modulation and thus resulting in continuous modulation duty cycles of 0 or 100%. The linear region of operation is unique to the saturating amplifier and PWM controlled



SUMMARY

Type of Input	STEP
Start Time	0.00000
Stop Time	0.04000
KP	1.00000
KV	0.00000
Ess	0.25000
GAIN	0.50000
PWM Freq (Hz)	2000.0

Figure 6.10 Phase Plane / Typical PWM Controller

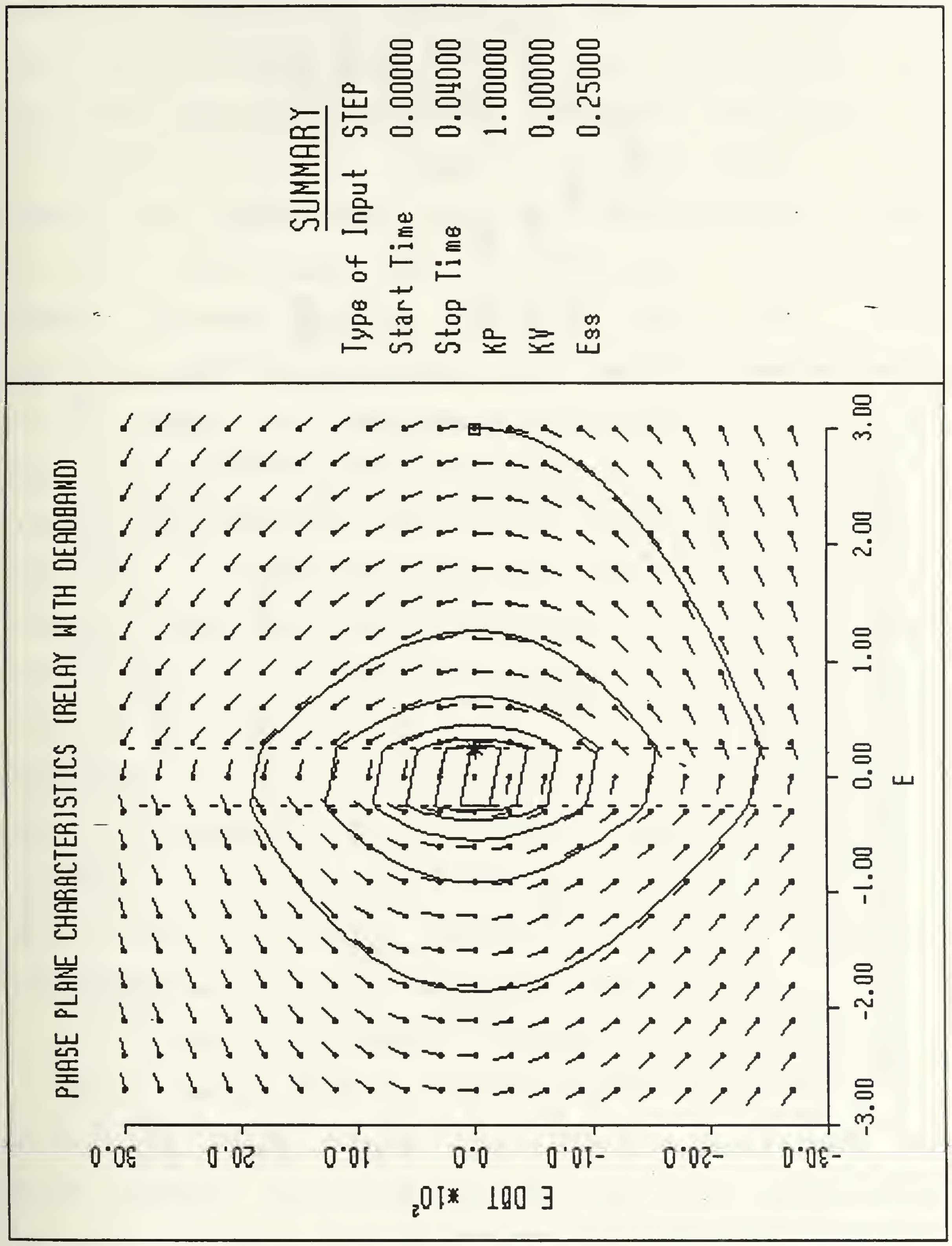


Figure 6.11 Phase Plane / Equivalent Relay Controller

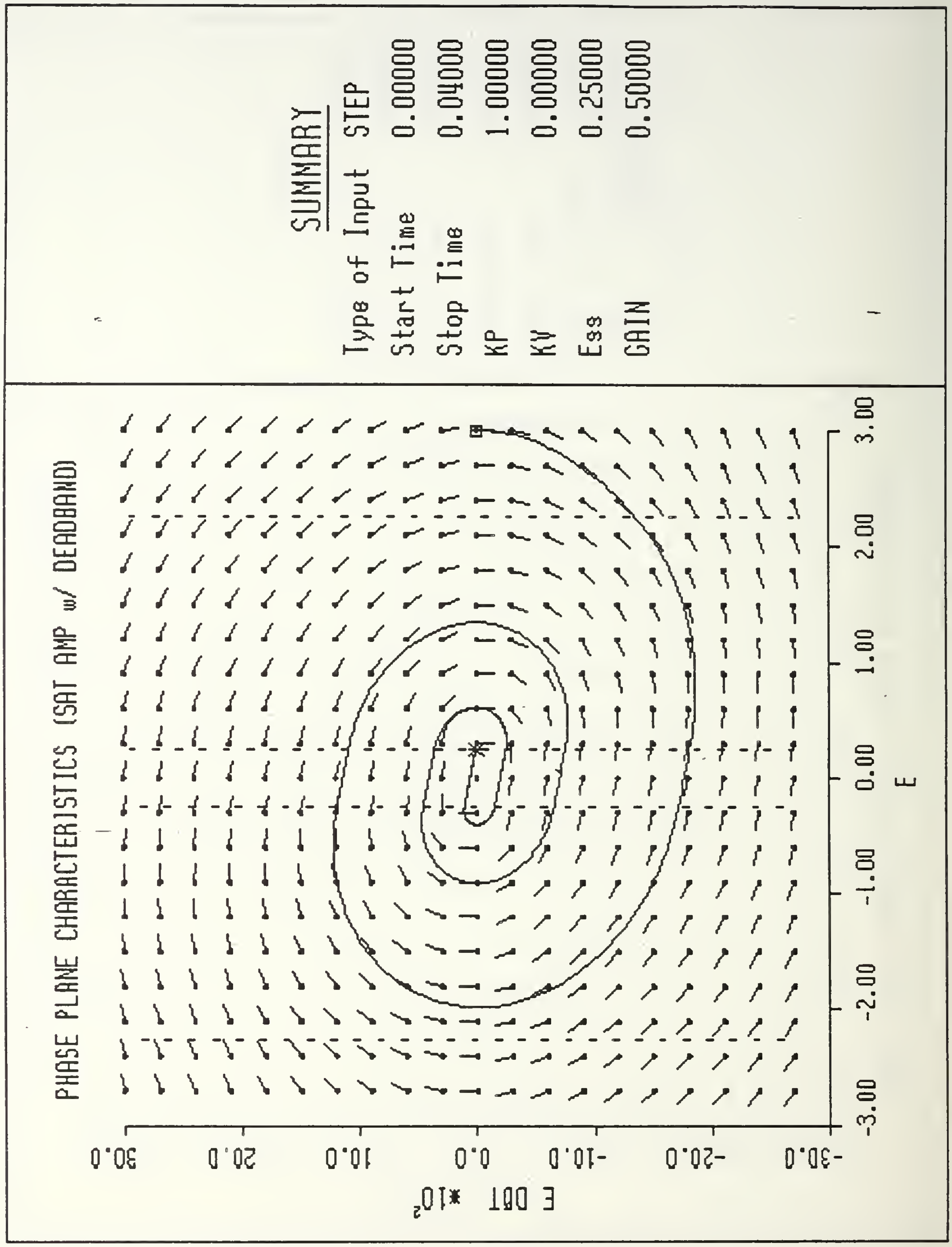


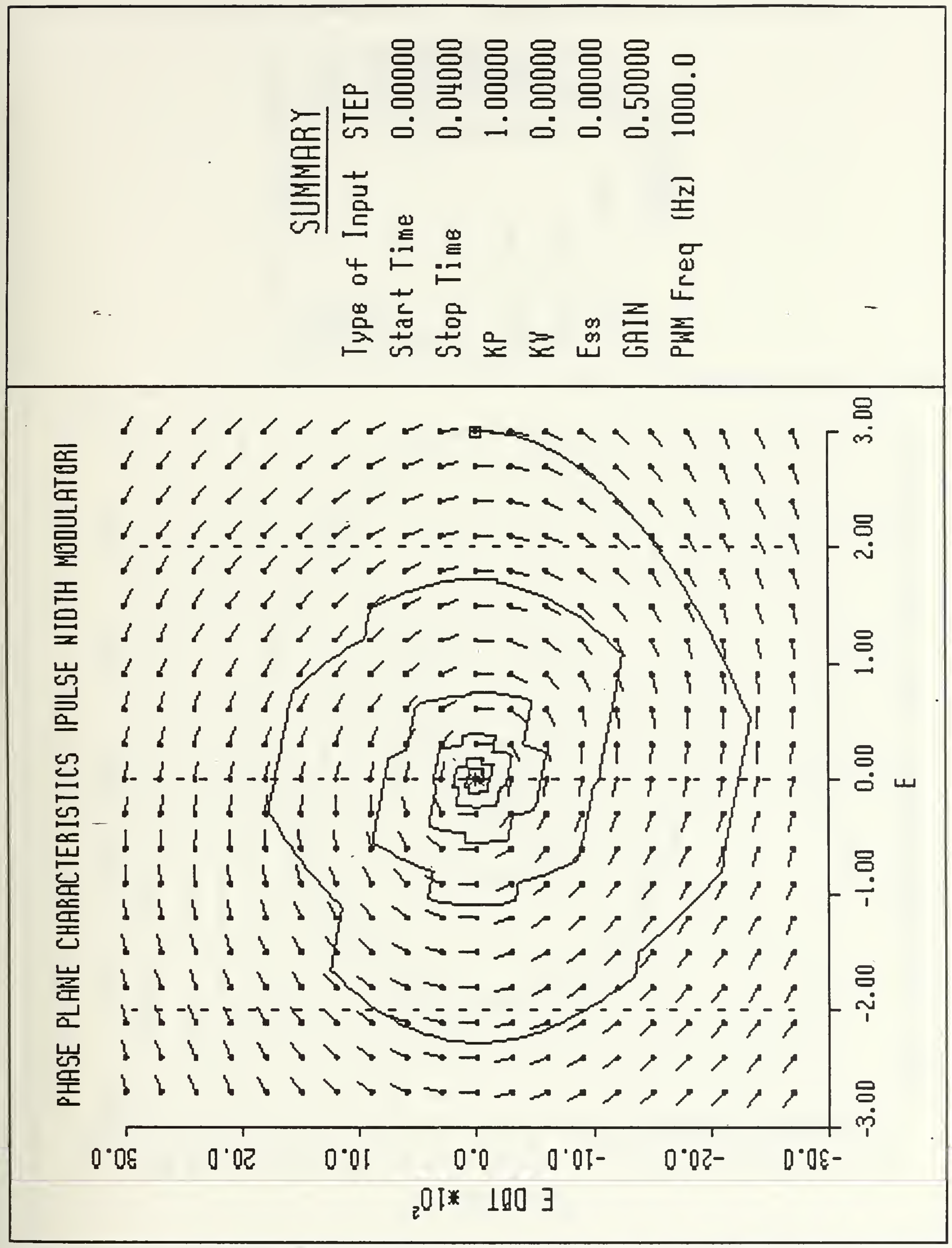
Figure 6.12 Phase Plane / Equivalent Saturation Amplifier Controller

systems. Although the phase plane portraits representing these two configurations are defined identically, the relatively low pulsing frequency exaggerates the effects of the discontinuous PWM. Specifically, the pulsing period used in the response of Figure 6.10 is sufficiently large so as to cause undesirably long durations of forced and natural response for a determined duty cycle. The increased significance of the time dimension in the phase plane results in time averaging being a less valid approximation of actual performance. If the trajectory in the linear region of the PWM of Figure 6.10 was time averaged, it would describe the same response as the saturating amplifier shown in Figure 6.12. However, the instantaneous and erratic trajectory of Figure 6.10 follows the path of the relay of Figure 6.11 while being forced with 150 volts and, during the relaxed mode, the path of natural response of the dead zone. Since the continuous amplifier provides ideally smooth response behavior, a maximum value of pulsing frequency is desired. Frequency considerations are discussed in subsequent trials.

The relative "softness" of the PWM's settling behavior is due to its relatively low value of amplifier gain. Small error values receive inadequate gain to provide the stiff control typically desired in high performance applications. Increasing amplifier gain approximates the stiff response of the relay shown in Figure 6.11.

The first design parameter to be independently examined in the phase plane was PWM pulse frequency. Although a maximum pulsing frequency of 10KHz was selected in Chapter V based on hardware limitations, the effect of pulse duration on system response is significant and deserves attention. Figures 6.13 through 6.16 illustrate the effects of varying f_{PWM} with values of 1, 5, 10, & 20KHz. Amplifier gain remains small so as to expand the linear region where pulsing frequency affects the response. All observations made during the trial describe the simulated trajectory in the linear region of operation.

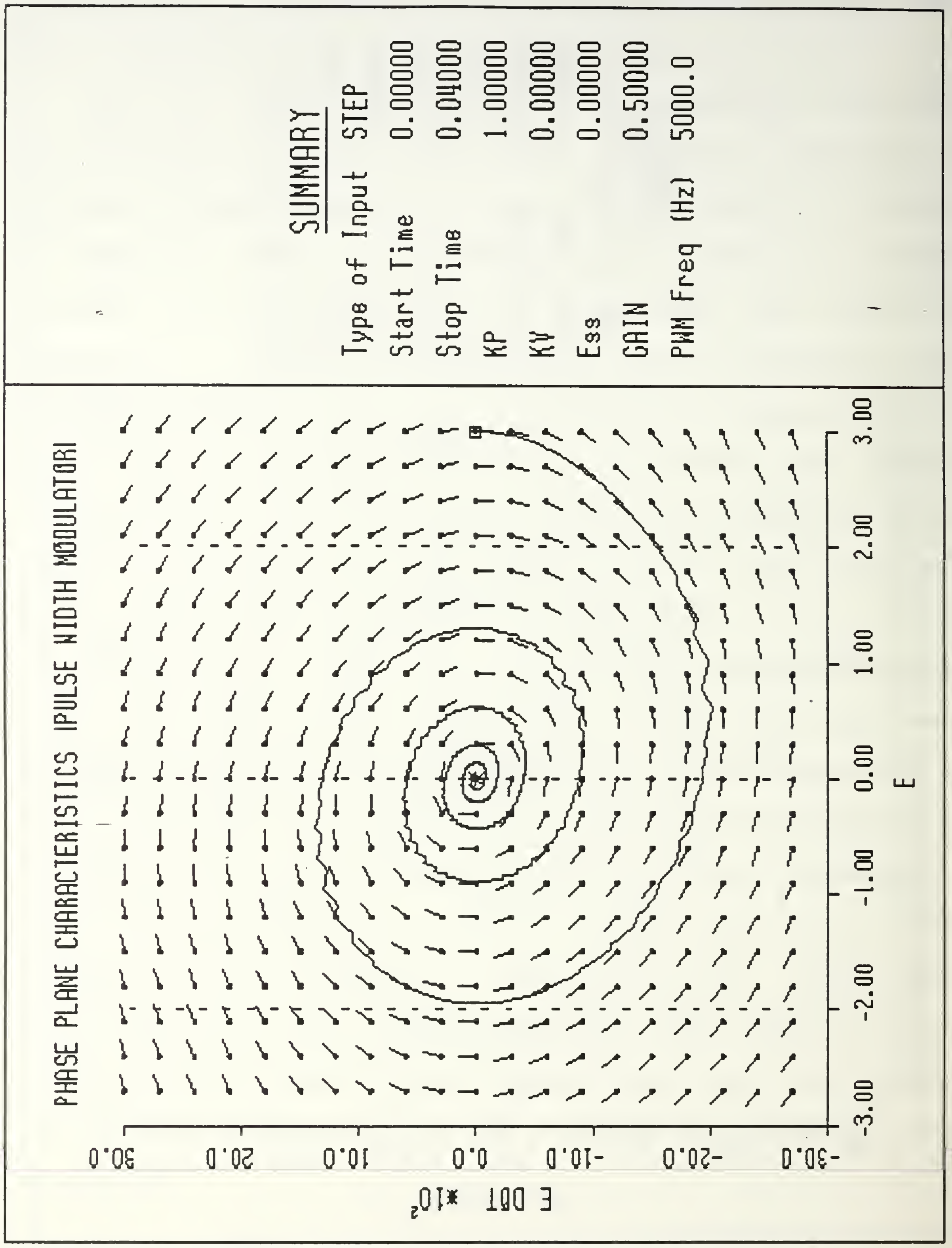
Figure 6.13 shows the unacceptable consequences of using an insufficient f_{PWM}. Poor correlation between portrait and trajectory characteristics implies the invalid time averaging is attributed to excessive pulse duration. The response is smoothed with higher pulsing frequencies. However, the difference between the 10 KHz and 20 KHz responses is negligible, indicating that very high frequencies are not required for the linear approximation of continuous saturation amplification to be valid. Therefore, 10 KHz was selected as optimum for PWM pulsing frequency.



SUMMARY

Type of Input	STEP
Start Time	0.00000
Stop Time	0.04000
KP	1.00000
KV	0.00000
Ess	0.00000
GAIN	0.50000
PWM Freq (Hz)	1000.0

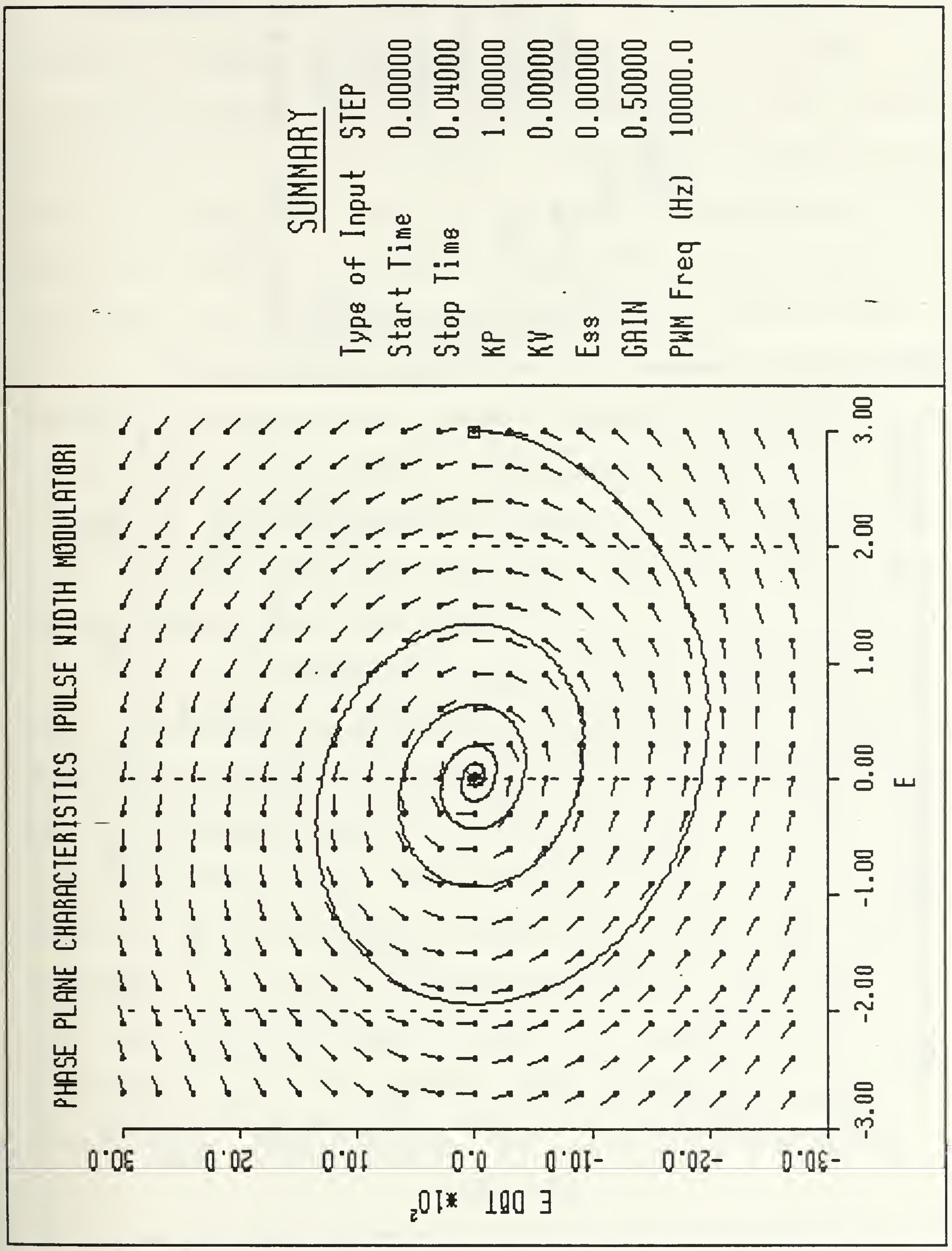
Figure 6.13 Phase Plane Response of 1KHz PWM Controller



SUMMARY

Type of Input	STEP
Start Time	0.00000
Stop Time	0.04000
KP	1.00000
KV	0.00000
Ess	0.00000
GAIN	0.50000
PWM Freq (Hz)	5000.0

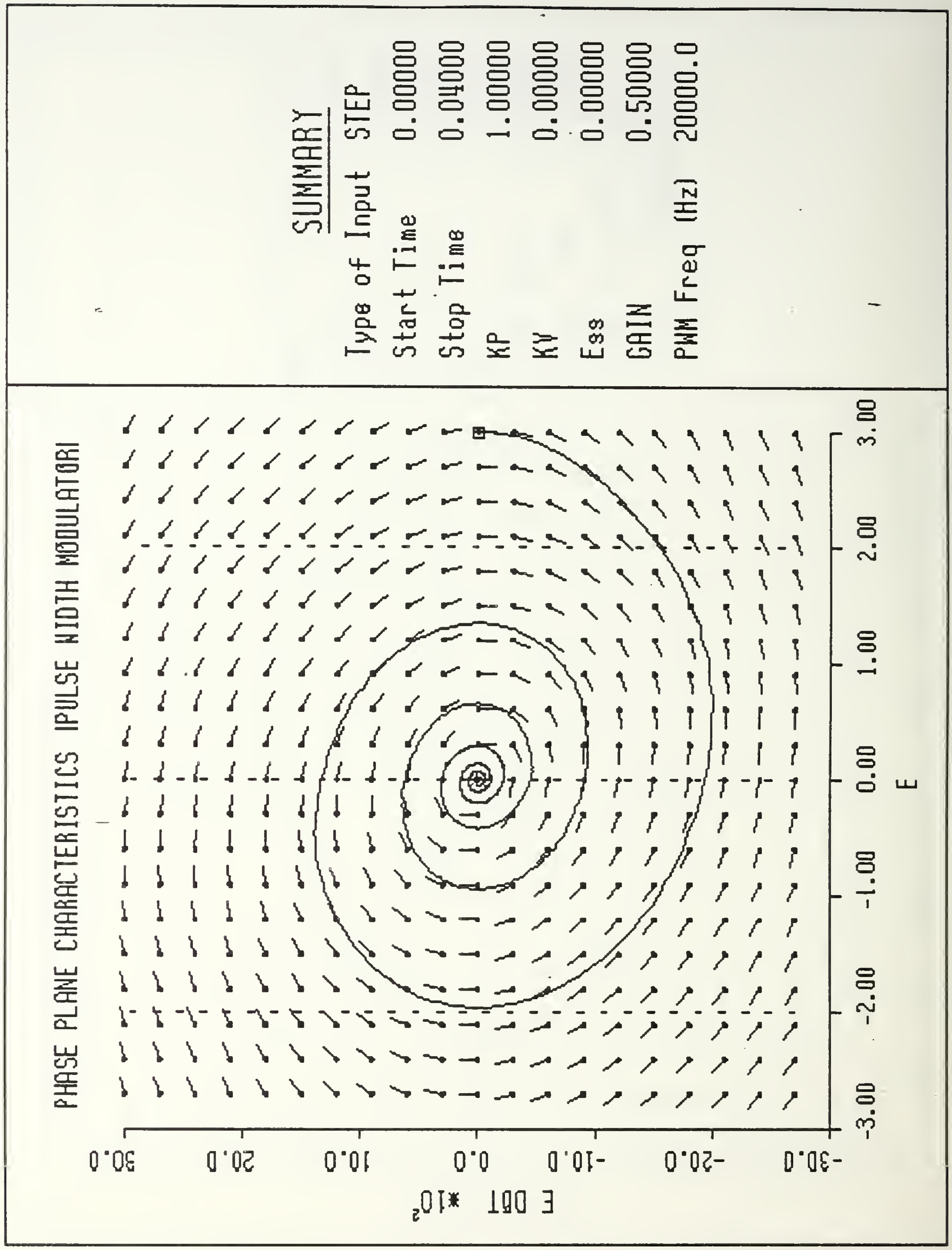
Figure 6.14 Phase Plane Response of 5KHz PWM Controller



SUMMARY

Type of Input	STEP
Start Time	0.00000
Stop Time	0.04000
KP	1.00000
KV	0.00000
Ess	0.00000
GAIN	0.50000
PWM Freq (Hz)	10000.0

Figure 6.15 Phase Plane Response of 10KHz PWM Controller



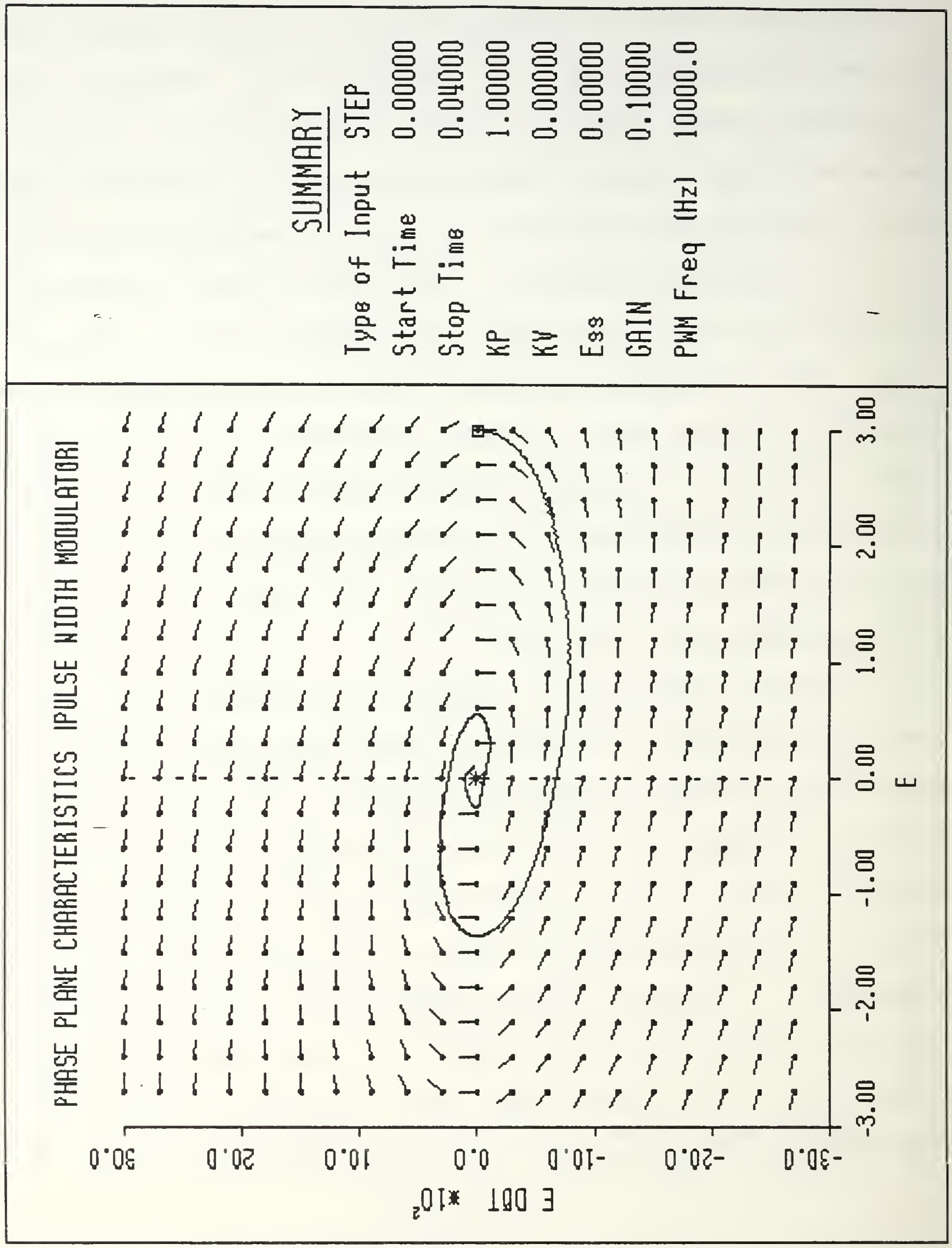
SUMMARY

Type of Input	STEP
Start Time	0.00000
Stop Time	0.04000
KP	1.00000
KV	0.00000
Ess	0.00000
GAIN	0.50000
PWM Freq (Hz)	20000.0

Figure 6.16 Phase Plane Response of 20KHz PWM Controller

Amplifier gain determines to a large extent the system's responsiveness. Figures 6.17 through 6.19 illustrate system behavior ranging from "soft" to "stiff". Relatively soft behavior shown in Figure 6.17 is due to the use of an amplifier gain of 0.1 and is characterized by a slow oscillatory transient. Conversely, stiff conditions are shown in Figure 6.19 and are attained using a K_{PWM} of 10.0. The trajectory resembles the response of the relay shown in Figure 6.11 and is described by very rapid "chattering" of the motor about steady state. Finally, acceptable responsiveness is achieved using a gain of 3.0 as illustrated in Figure 6.18 and, therefore, was selected as the optimum value for gain.

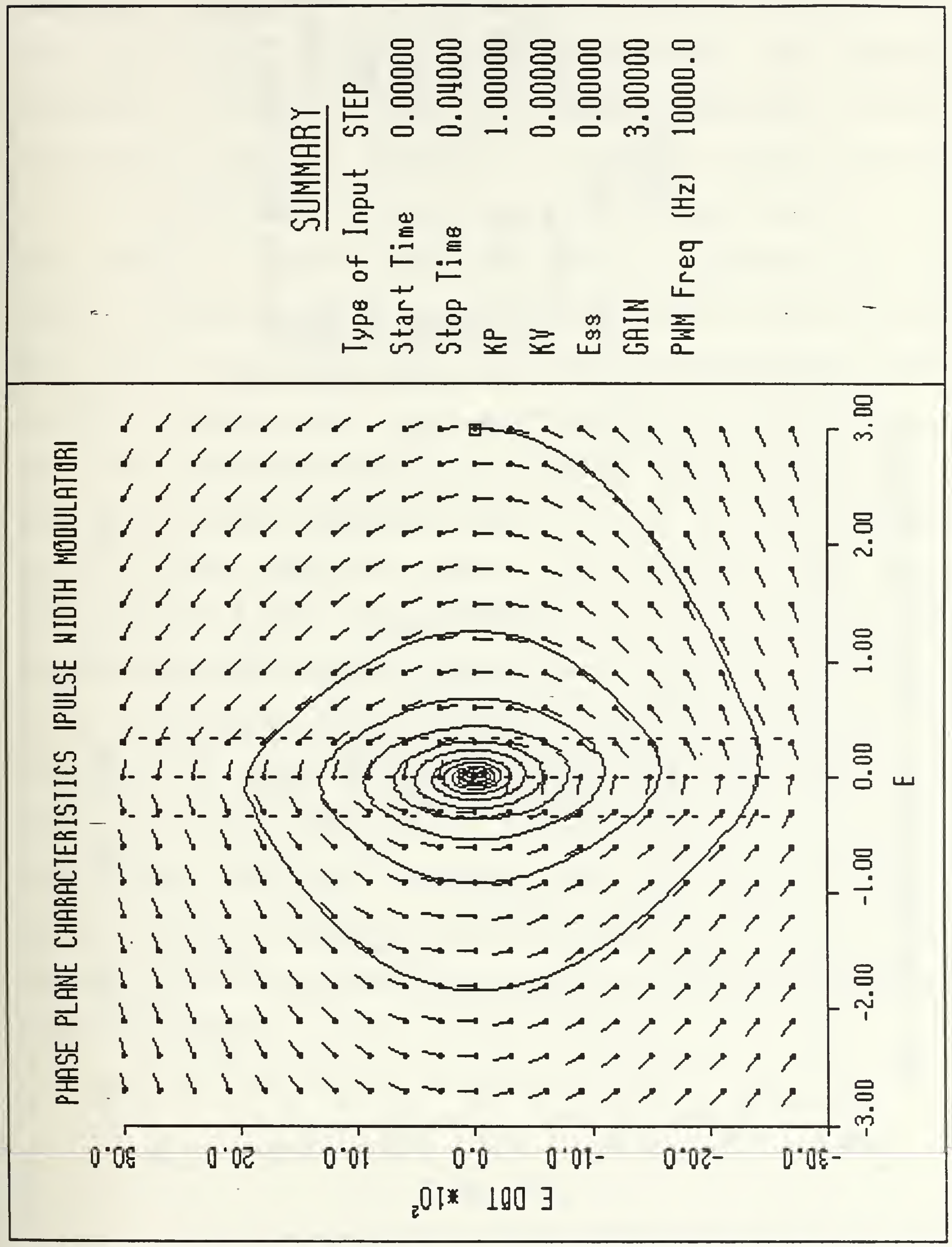
A pulsing frequency of 10KHz and amplifier gain of 3 were independently selected by observing their effects on phase plane response behavior. However, frequency and gain exhibit coupled effects which result in limit cycle behavior. While limit cycles may not be eliminated solely through the selection of K_{PWM} and f_{PWM}, they may be minimized. Steady state oscillations are small in amplitude for the parameter selection described. However, when gain is increased and frequency decreased, unacceptable magnification of limit cycle behavior is



SUMMARY

Type of Input	STEP
Start Time	0.00000
Stop Time	0.04000
KP	1.00000
KV	0.00000
Ess	0.00000
GAIN	0.10000
PWM Freq (Hz)	10000.0

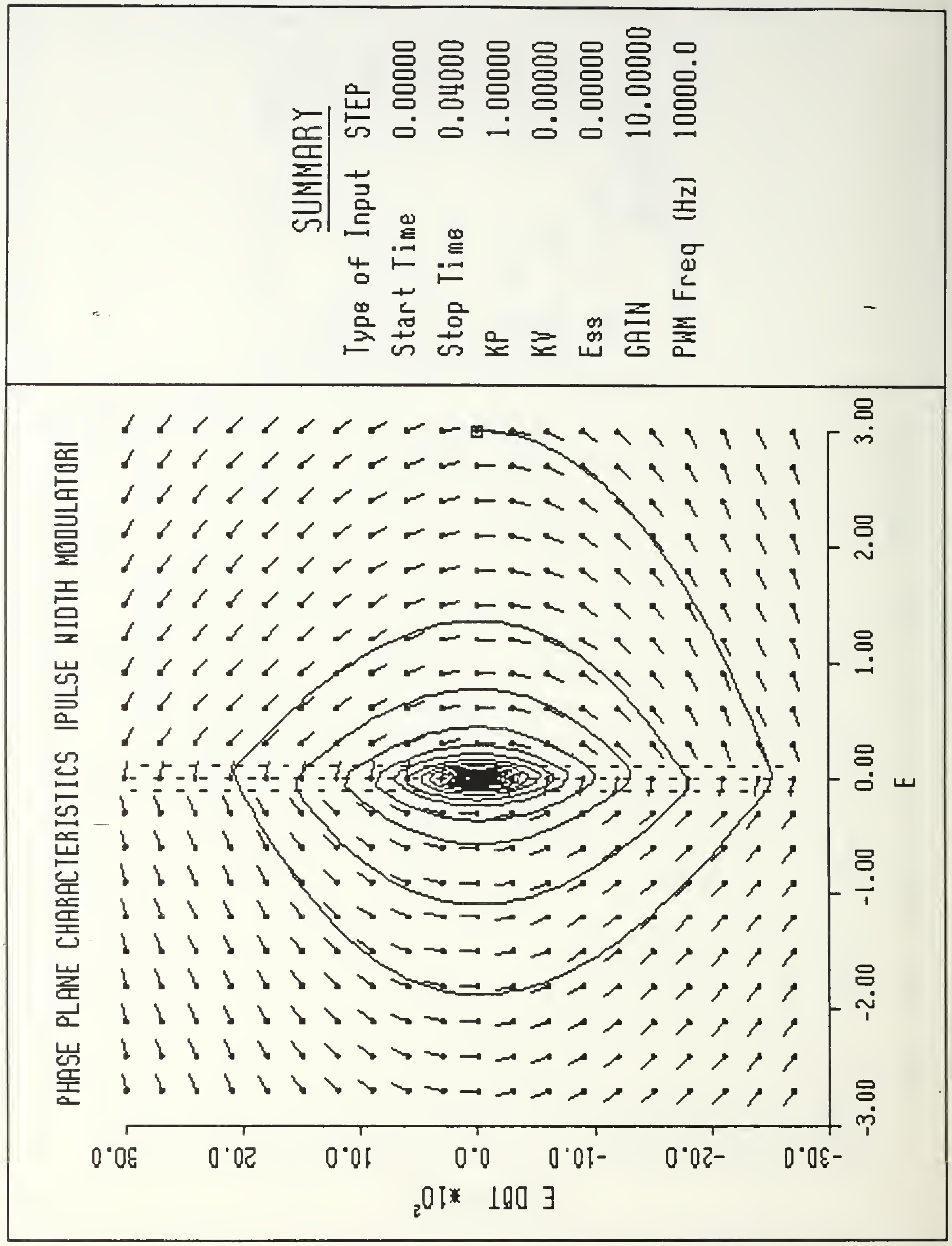
Figure 6.17 Phase Plane Response of K_{PWM}=.1 PWM Controller



SUMMARY

Type of Input	STEP
Start Time	0.00000
Stop Time	0.04000
KP	1.00000
KV	0.00000
Ess	0.00000
GAIN	3.00000
PWM Freq (Hz)	10000.0

Figure 6.18 Phase Plane Response of K_{PWM}=3. PWM Controller



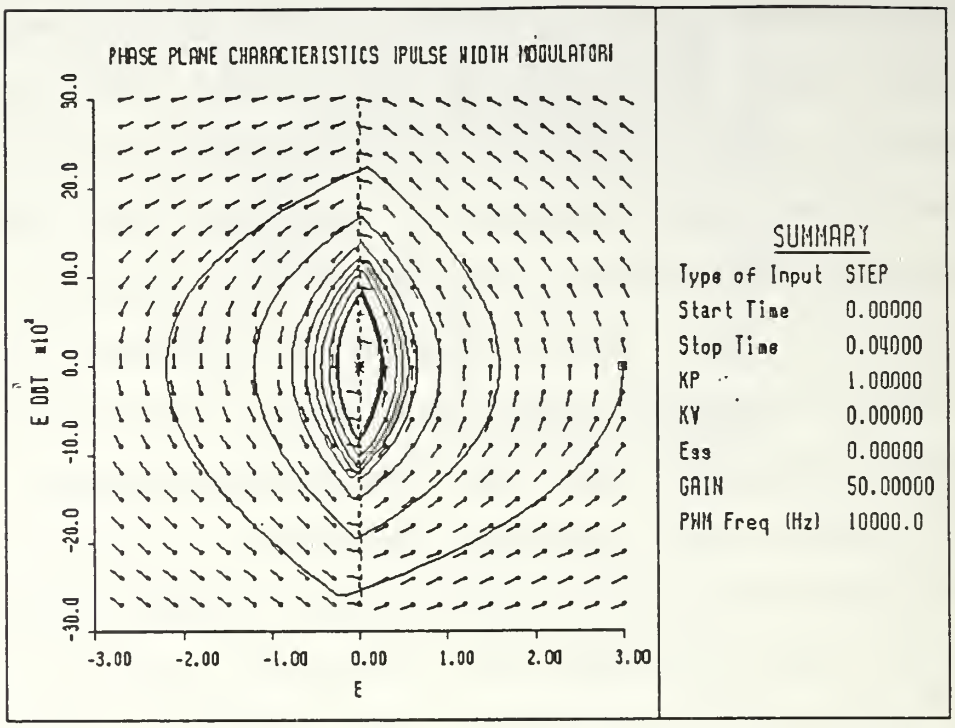
SUMMARY

Type of Input	STEP
Start Time	0.00000
Stop Time	0.04000
KP	1.00000
KV	0.00000
Ess	0.00000
GAIN	10.00000
PWM Freq (Hz)	10000.0

Figure 6.19 Phase Plane Response of $K_{PWM}=10$ PWM Controller

realized. Figure 6.20 illustrates the effect of increasing amplifier gain to 50 while maintaining the pulsing frequency at 10KHz. Figure 6.21 shows exaggerated effects achieved by reducing frequency to 1KHz with gain fixed at 3. The region shown by the circle is discussed below.

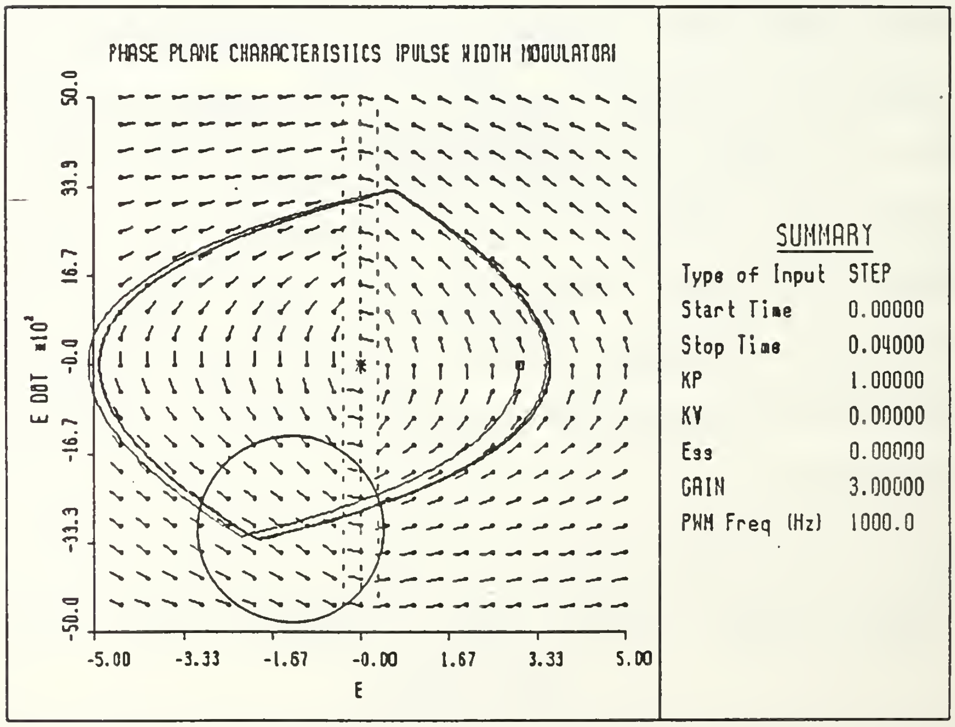
The extent of limit cycle behavior is dependent on the amount of electromotive energy provided to the motor during the delay associated with the PWM pulsing period. For example, consider the low f_{PWM} trajectory of Figure 6.21. The delay observed in actual controller switching caused by the finite pulse duration which extends the state space forcing vector from one region into another. The delay highlighted by the circular region in Figure 6.21 may be graphically observed in Figure 6.22 by examining the pulse width modulator's time response in the the proximity of switching. Once a pulse's duty cycle is set, the controller is temporarily insensitized to operating conditions for the remainder of the pulse period. Interpretation of Figure 6.22 confirms that limit cycle behavior may be reduced by increasing pulsing frequency or decreasing gain.



SUMMARY

Type of Input	STEP
Start Time	0.00000
Stop Time	0.04000
KP	1.00000
KV	0.00000
Ess	0.00000
GAIN	50.00000
PWM Freq (Hz)	10000.0

Figure 6.20 Stable Limit Cycle Due to $K_{PWM}=50$.



SUMMARY

Type of Input	STEP
Start Time	0.00000
Stop Time	0.04000
KP	1.00000
KV	0.00000
Ess	0.00000
GAIN	3.00000
PWM Freq (Hz)	1000.0

Figure 6.21 Stable Limit Cycle Due to f_{PWM}=1KHz

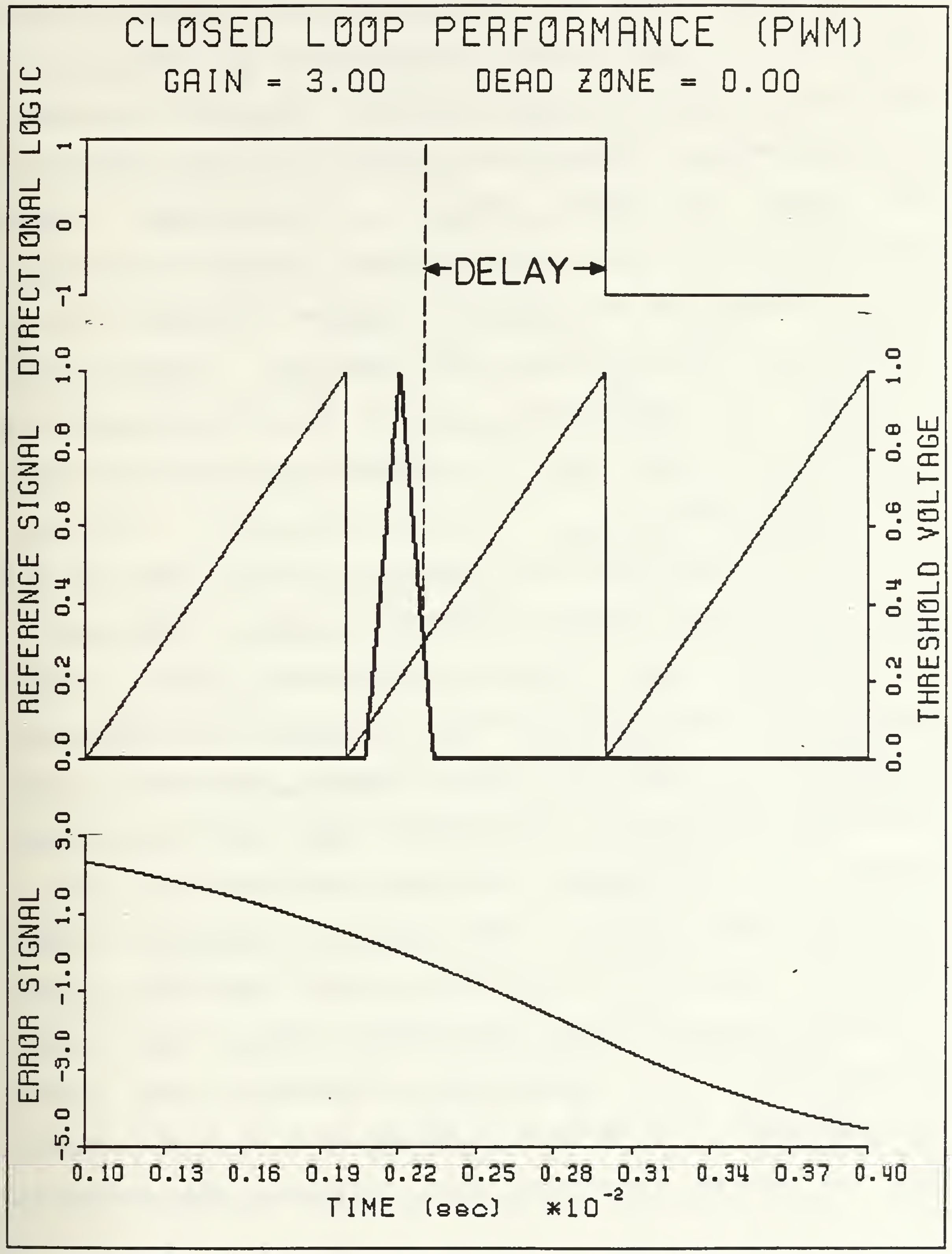
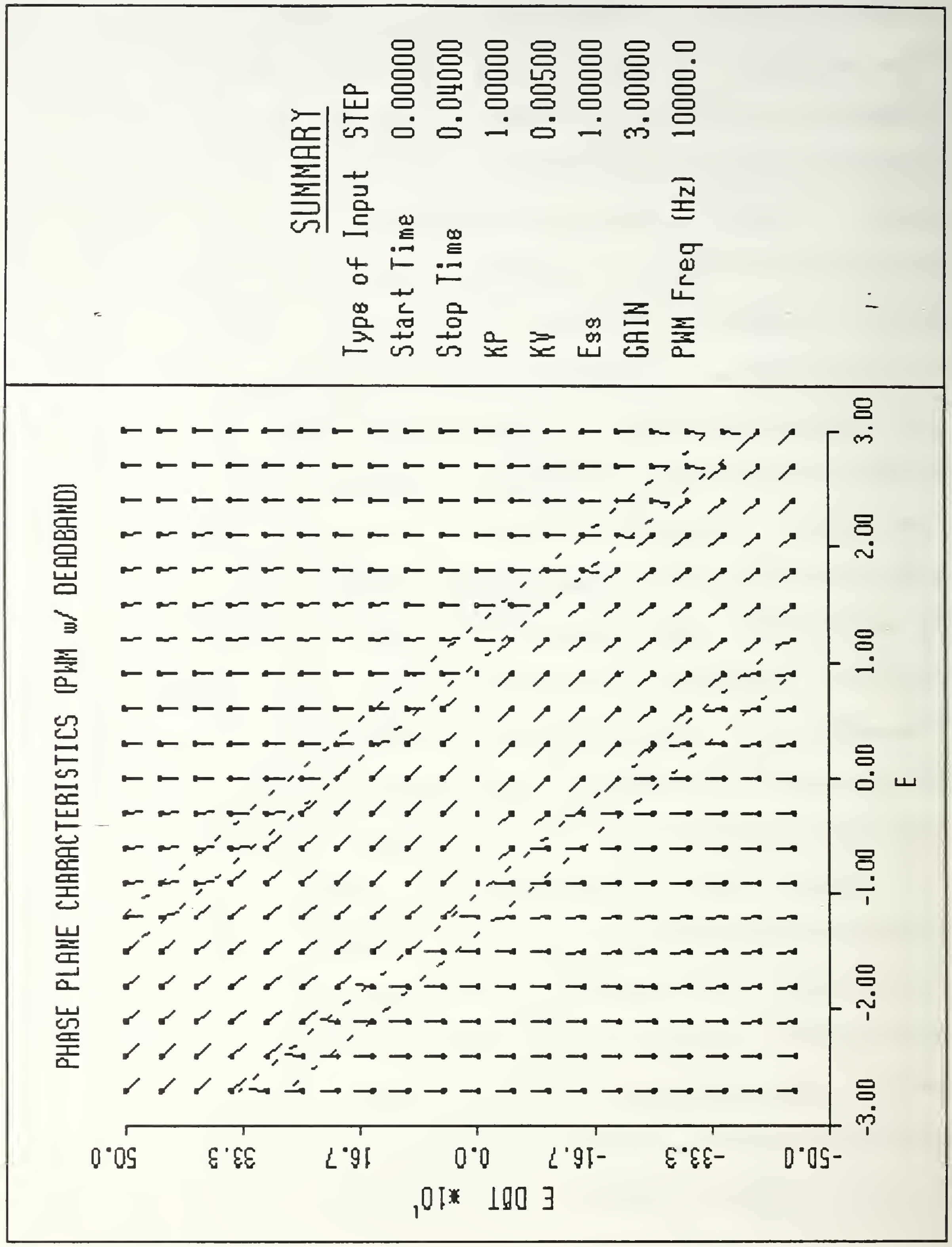


Figure 6.22 PWM Time Response Describing Switching Delay

The final phase of this preliminary design involves selection of feedback gain coefficients K_p and K_v. For analytical simplicity, unity feedback ($K_p = 1$) is chosen. Velocity feedback is selected relative to K_p and determines the extent of system damping. The feedback design performed in the phase plane does not incorporate dead zone in the controller for the sole purpose of enhancing the illustration of switching line behavior. Specifically, reticence, or "chattering", is not desired and might be undetected if dead zone is applied in this preliminary stage of the design.

Lines of discontinuity acquire a finite slope in the phase plane when velocity feedback is used. The slope is the feedback ratio, $-K_p/K_v$, and applies to all region boundaries. Trajectory interaction with the switching line provides the definition for damping criteria. For continuous regulators, sufficiently large velocity feedback results in overdamped behavior characterized by no transient oscillation. The system trajectory should approach, but not intersect, the switching line. Overdamping discontinuous controllers, such as the PWM, is characterized by excessive reticence and slow responsiveness. If velocity feedback gain is small enough, then the system trajectory will intersect the switching line and yield an underdamped oscillatory transient. The intersection of the $\dot{e}$-axis by the trajectory defines transient overshoot. Critical damping is described by the condition where the trajectory coincides with the switching line. The phase plane provides a graphic method of selection of damping characteristics. It is observed that slope markers, which represent system response characteristics unique to specific operating conditions, are independent of K_V. Furthermore, region #1 of Table IV describes the system's natural response found in dead zone operation. Alignment of the K_V dependent switching line (dashed line) with slope markers in the dead zone is shown in the phase plane portrait of Figure 6.23 and results in critical damping. The switching line slope may be increased by decreasing K_V, resulting in underdamped conditions. Conversely, increasing K_V tends the switching line towards horizontal and yields overdamped behavior.

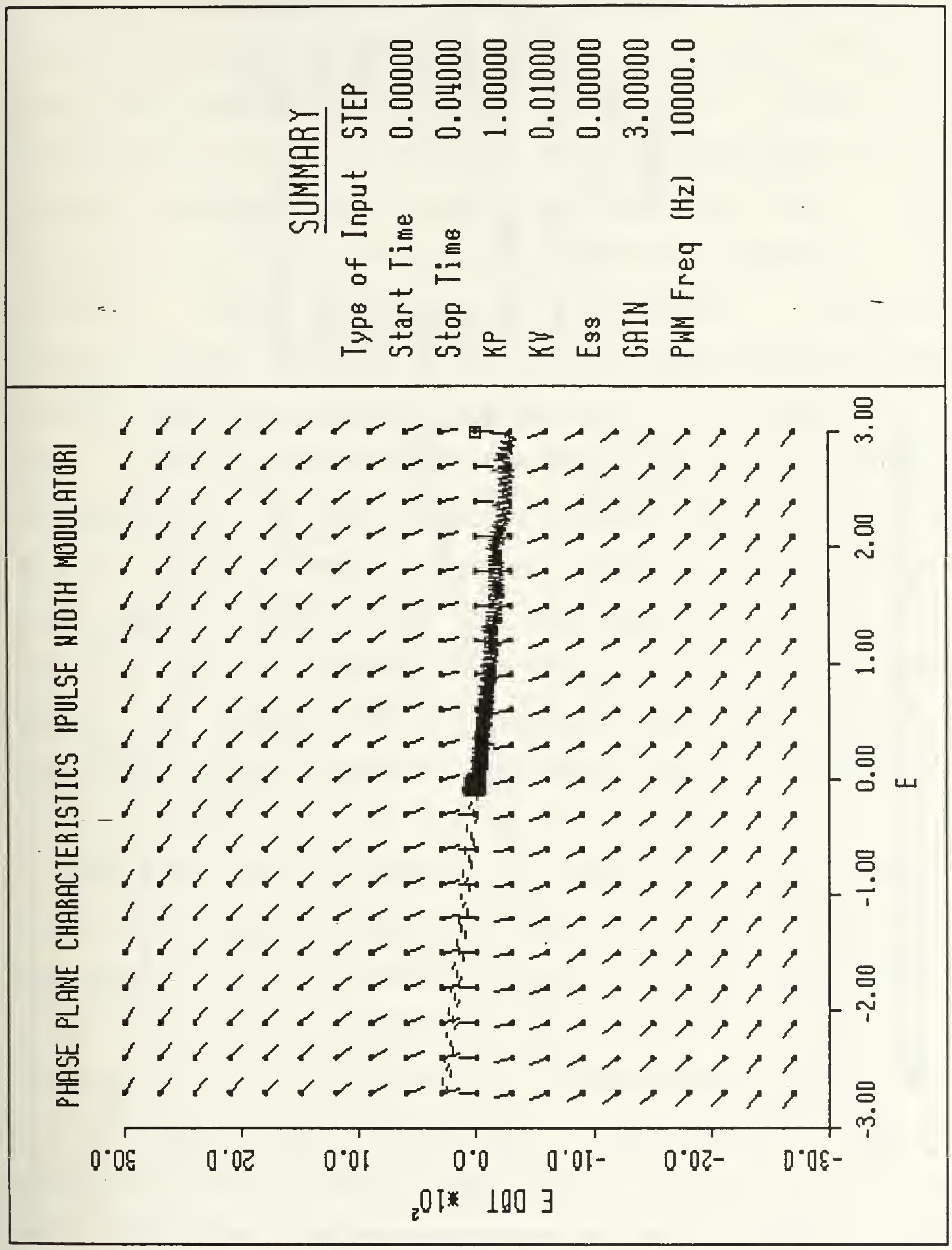
Figure 6.24 illustrates overdamped step response behavior attained with a velocity feedback gain coefficient of K_V=0.01. The trajectory is characterized by excessive "chattering" while it slowly traverses the switching line and is associated with large K_V. Near critical damping is shown in Figure 6.25 where K_V=0.005 and is characterized by slow transient behavior along the switching line. This



SUMMARY

Type of Input	STEP
Start Time	0.00000
Stop Time	0.04000
KP	1.00000
KV	0.00500
Ess	1.00000
GAIN	3.00000
PWM Freq (Hz)	10000.0

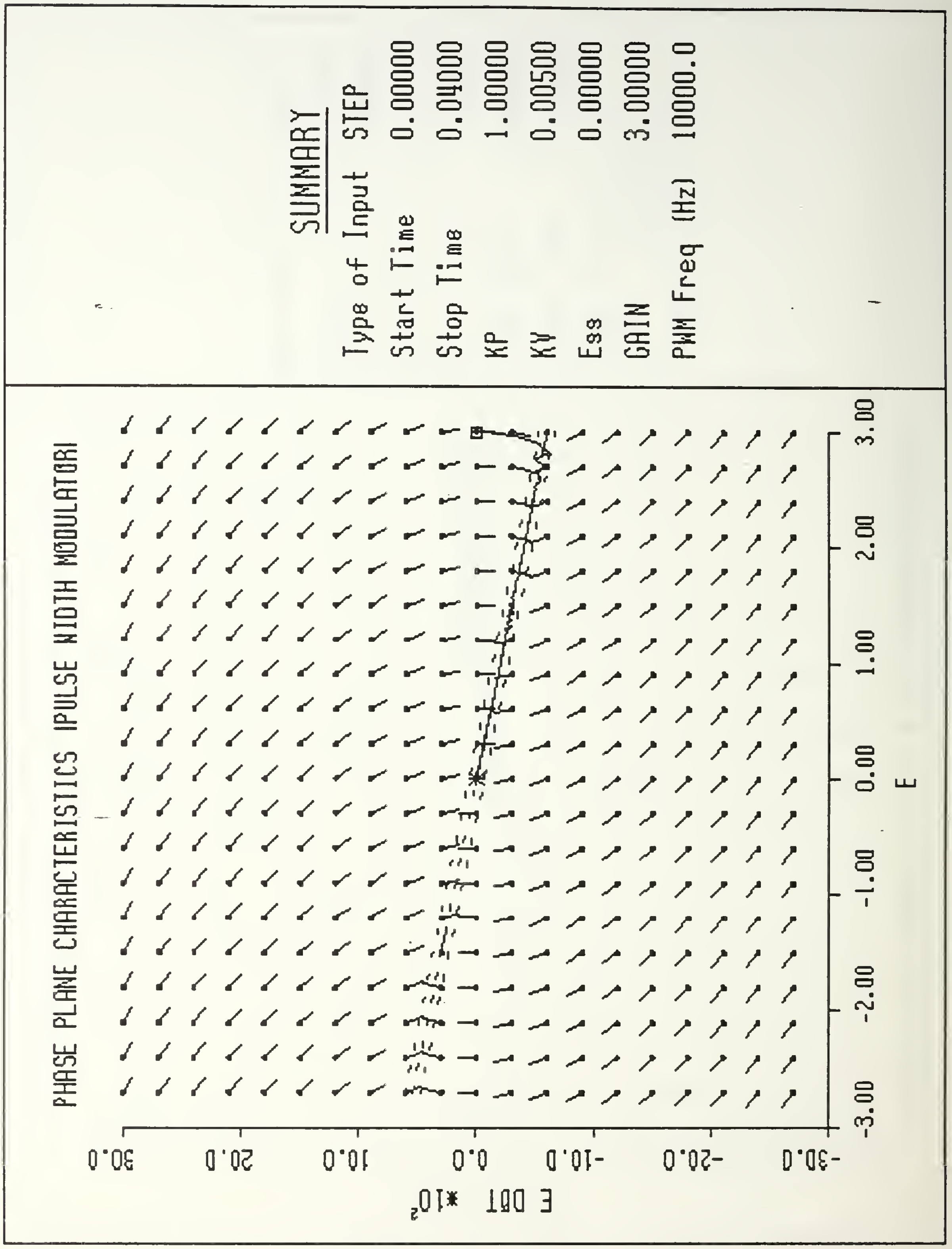
Figure 6.23 Phase Plane Portrait Showing Natural Response



SUMMARY

Type of Input	STEP
Start Time	0.00000
Stop Time	0.04000
KP	1.00000
KV	0.01000
Ess	0.00000
GAIN	3.00000
PWM Freq (Hz)	10000.0

Figure 6.24 Phase Plane / Overdamped Step Response



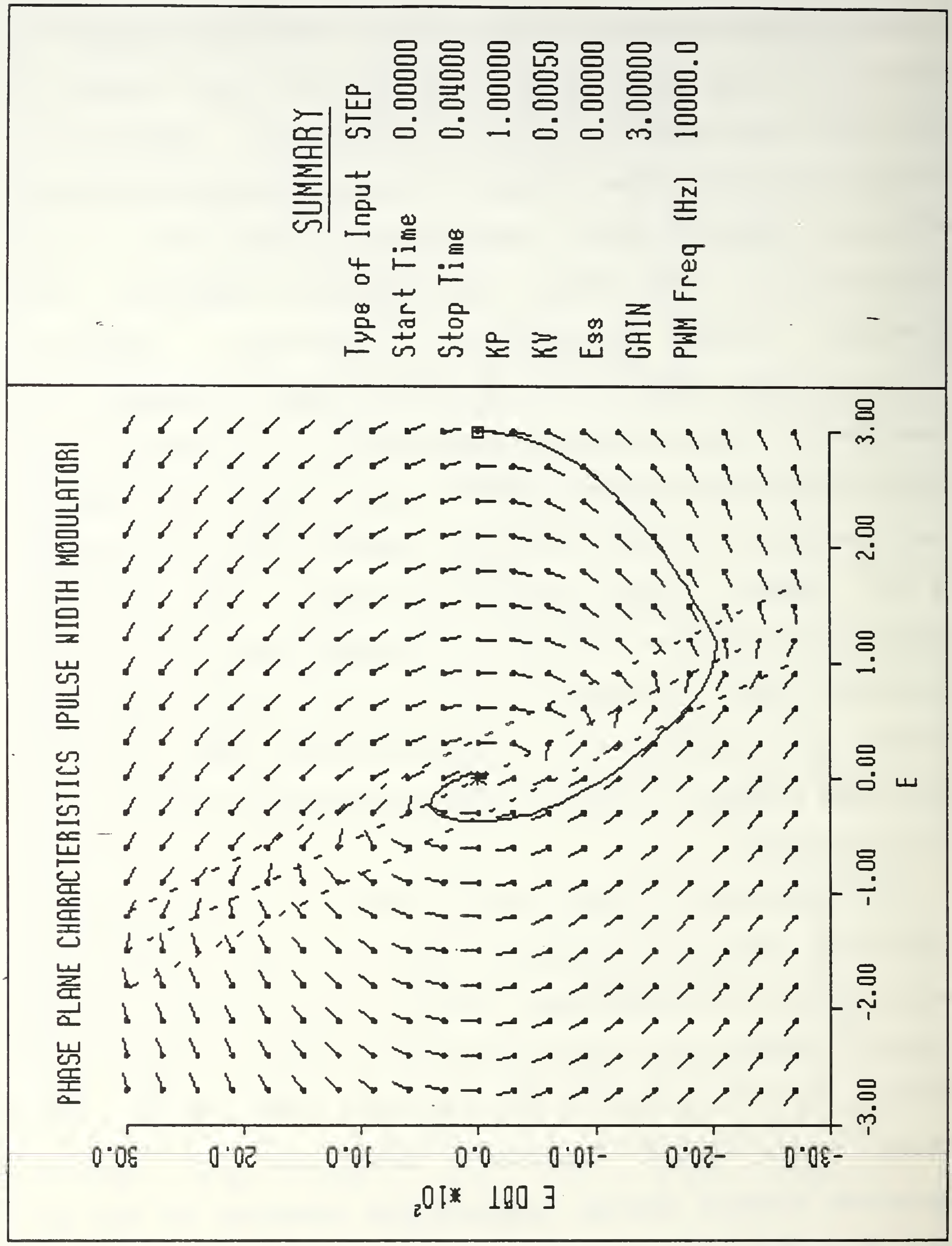
SUMMARY

Type of Input	STEP
Start Time	0.00000
Stop Time	0.04000
KP	1.00000
KV	0.00500
Ess	0.00000
GAIN	3.00000
PWM Freq (Hz)	10000.0

Figure 6.25 Phase Plane / Critically Damped Step Response

system configuration provides optimal position control in terms of energy requirements, but is not well suited to this high performance tracking application. Figure 6.26 illustrates underdamped response behavior associated with a velocity feedback gain coefficient of K_v=0.0005. The trajectory is oscillatory and exhibits overshoot, but provides highly responsive transient behavior. Characteristics observed in the phase plane of Figure 6.27 describe good step response performance of fin position for the linearly approximated system when K_v=0.001 and support the selection of this velocity feedback gain coefficient as an optimal design parameter value. The slightly underdamped response shows no overshoot and has a fast settling time. Figures 6.28 and 6.29 show agreement between the reduced (2nd) order and third order systems' step time response, thereby validating results attained via the phase plane.

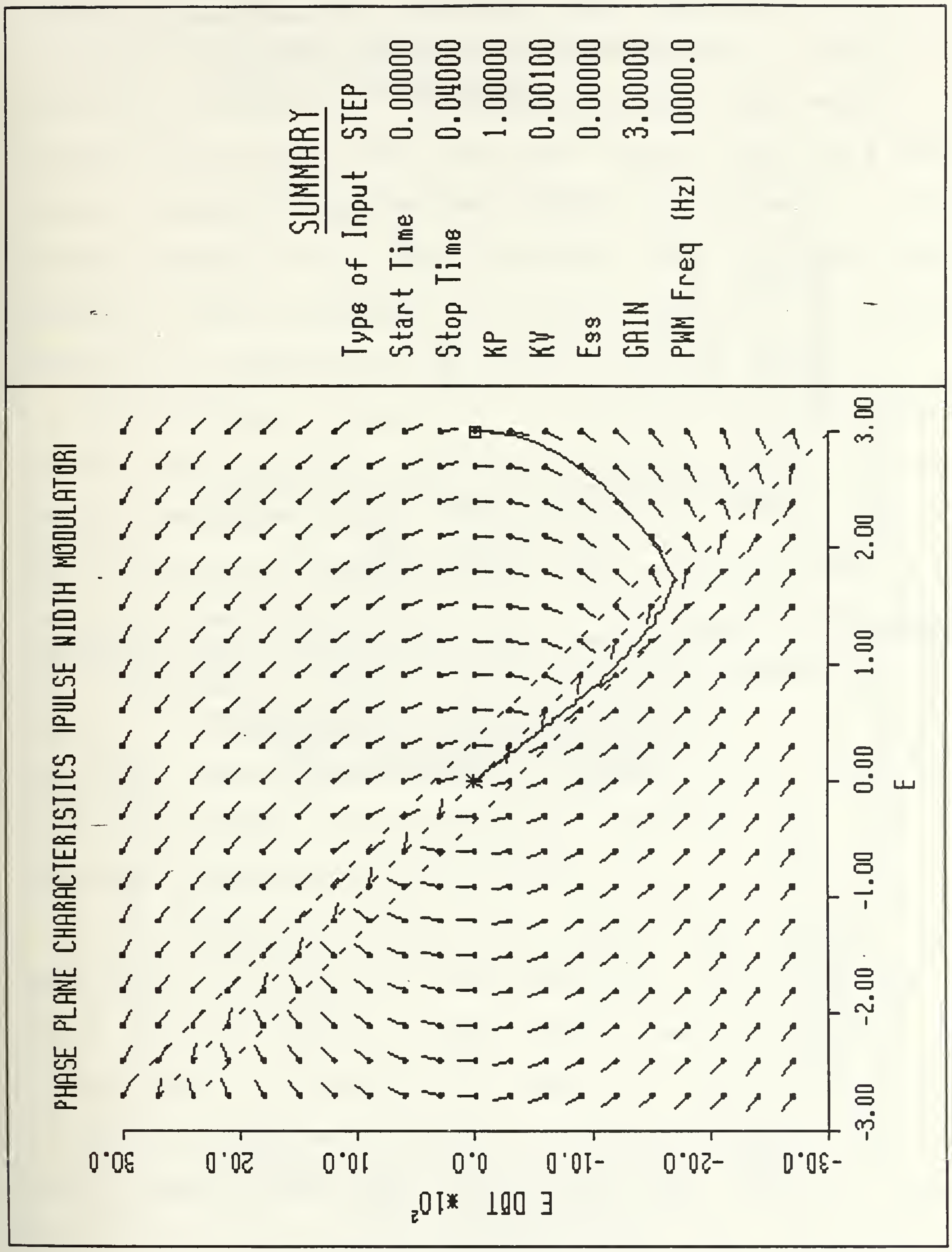
The phase plane described by e and $\dot{e}$ for step response conditions actually describes $-\theta_{fin}$ and $-\omega_{fin}$. The plane may readily be transformed into an energy plane, where potential energy is a function of e and kinetic energy is a function of $\dot{e}$. The switching line which passes through the steady state point describes conditions of locally maximized kinetic energy, whereas the crossing of the e-axis describes localized minimum kinetic energy. The



SUMMARY

Type of Input	STEP
Start Time	0.00000
Stop Time	0.04000
KP	1.00000
KV	0.00050
Ess	0.00000
GAIN	3.00000
PWM Freq (Hz)	10000.0

Figure 6.26 Phase Plane / Underdamped Step Response



SUMMARY

Type of Input	STEP
Start Time	0.00000
Stop Time	0.04000
KP	1.00000
KV	0.00100
Ess	0.00000
GAIN	3.00000
PWM Freq (Hz)	10000.0

Figure 6.27 Phase Plane / Preliminary Optimal Design Step Response

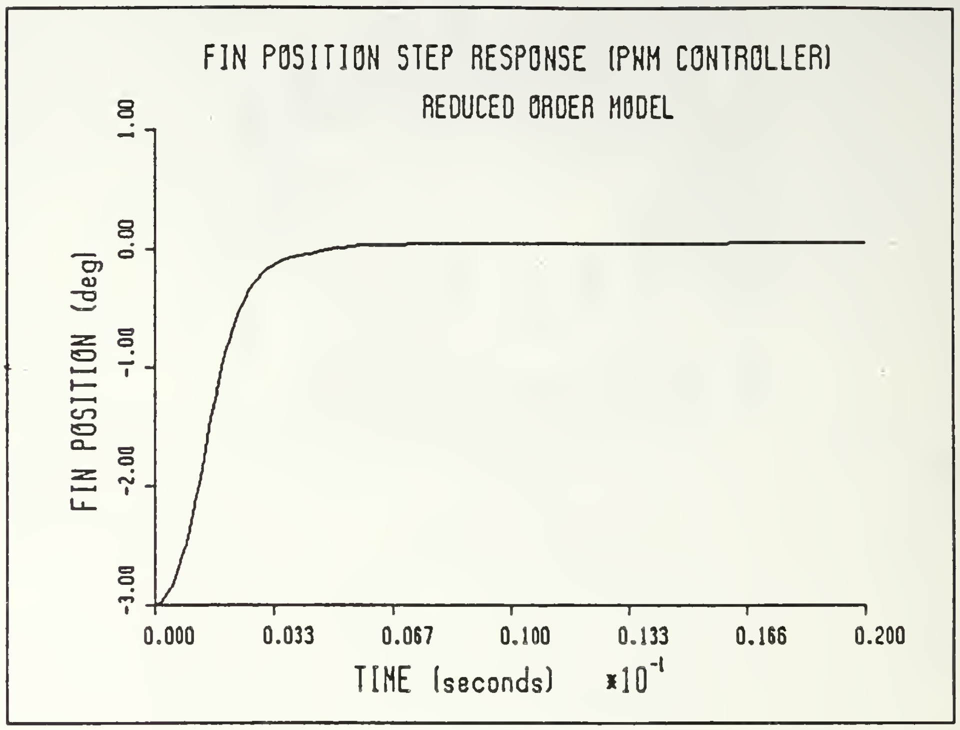


Figure 6.28 Reduced Order Model Fin Position Step Response

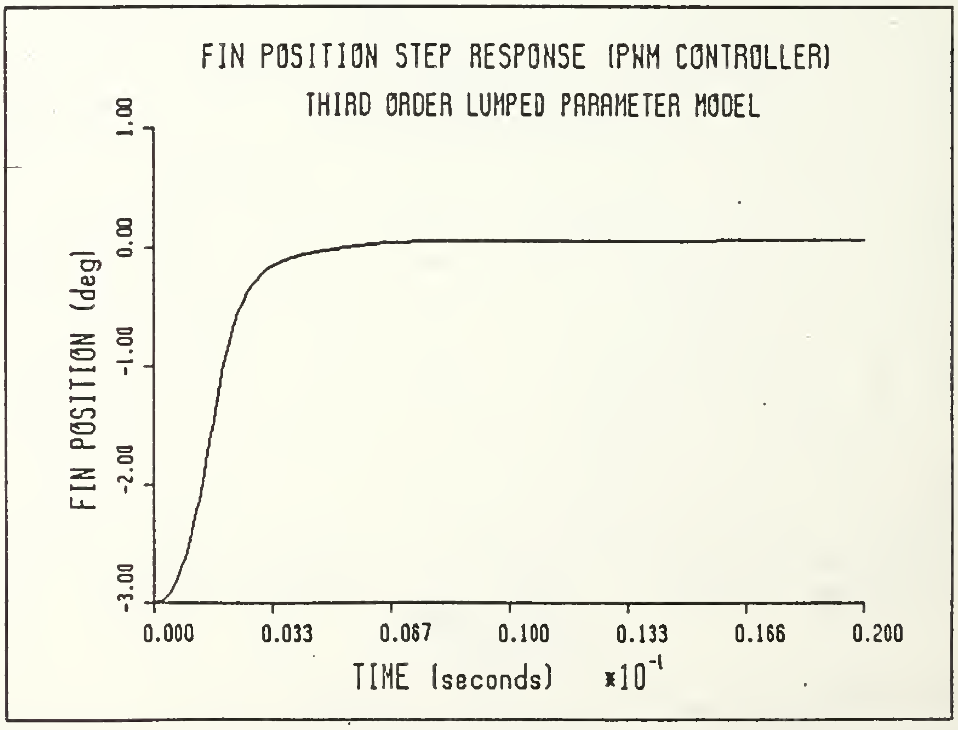
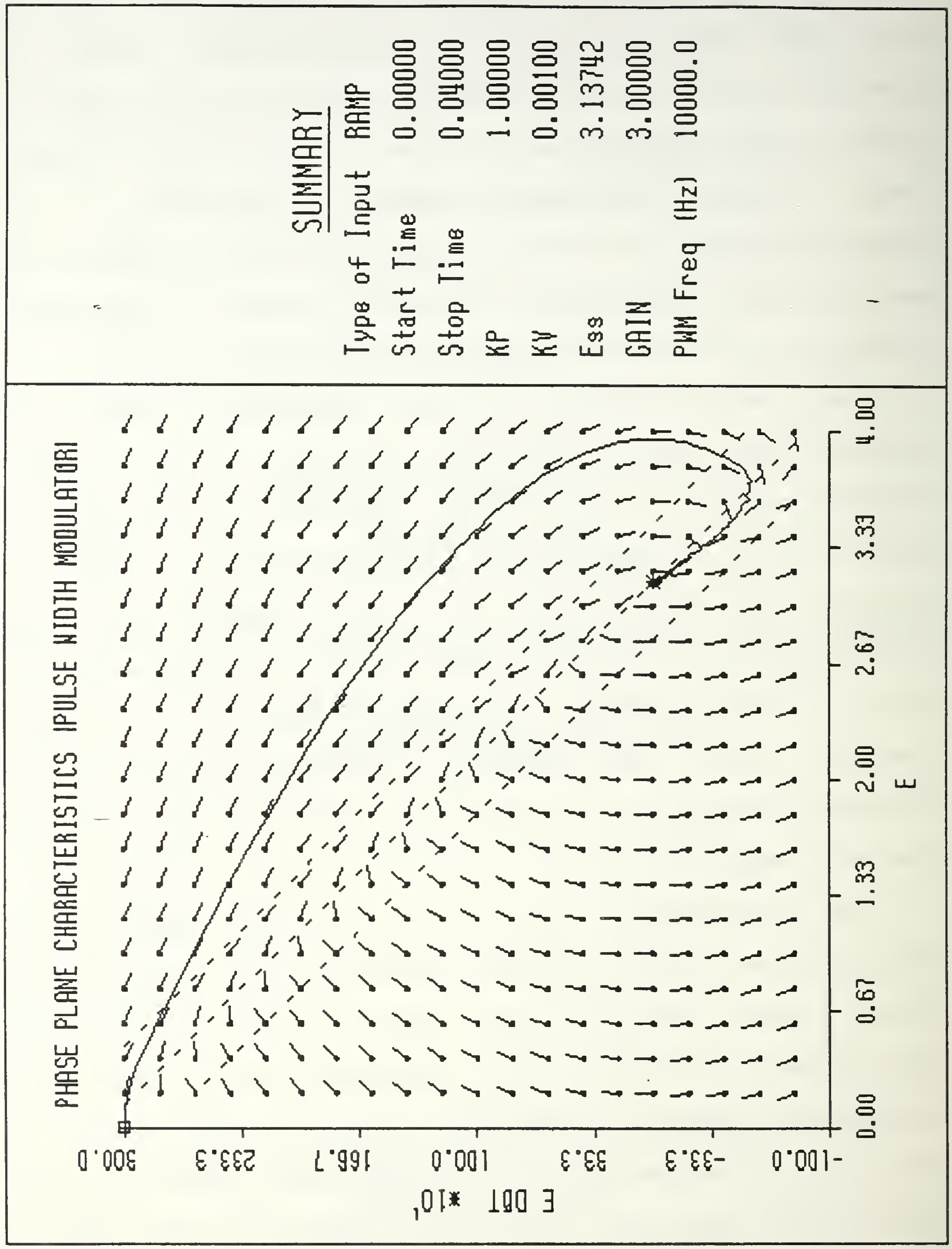


Figure 6.29 Third Order Model Fin Position Step Response

degree of response stiffness of the controller is determined by the amount of electromotive energy it provides to the motor. Increased amplifier gain results in greater pulse duty cycles for given system conditions and, hence, greater electromotive energy transmission. The forced harmonic oscillation frequency also increases with amplifier gain and results in greater numbers of rotational reversals, a condition to be avoided whenever possible.

Ramp response analysis is also supported by phase plane methods and will be briefly discussed. The natural response component of the slope function (η) described by Equation 6.20 is dependent on the ramp slope, $\dot{r}$. When $\dot{r}$ is non-zero, the coordinates $(e,\dot{e})$ do not linearly transform to $(-\theta_{fin},-\omega_{fin})$ and the energy plane correlation is not valid. Additionally, the phase plane is no longer symmetric about the e-axis. Consequently, the ramp response portrait is significantly different than that of the step response.

The underdamped controller whose step response was determined in Figure 6.27 was subjected to a ramp input of slope $\dot{r}$=3000 deg/sec. The phase plane trajectory is illustrated in Figure 6.30, characterized by similarly acceptable response behavior. Steady state error is analytically determined to be e_{ss}=3.14 by equation 6.21. Figures 6.31 and 6.32 provide the ramp time responses of



SUMMARY

Type of Input	RAMP
Start Time	0.00000
Stop Time	0.04000
KP	1.00000
KV	0.00100
Ess	3.13742
GAIN	3.00000
PWM Freq (Hz)	10000.0

Figure 6.30 Phase Plane / Preliminary Optimal Design Ramp Response

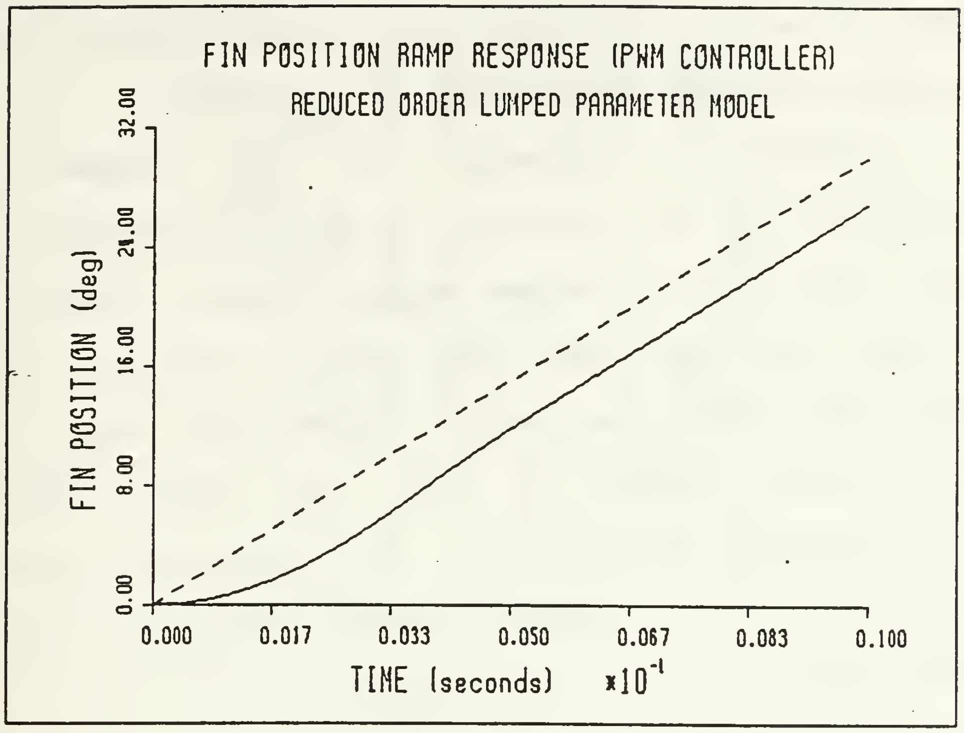


Figure 6.31 Reduced Order Model Fin Position Ramp Response

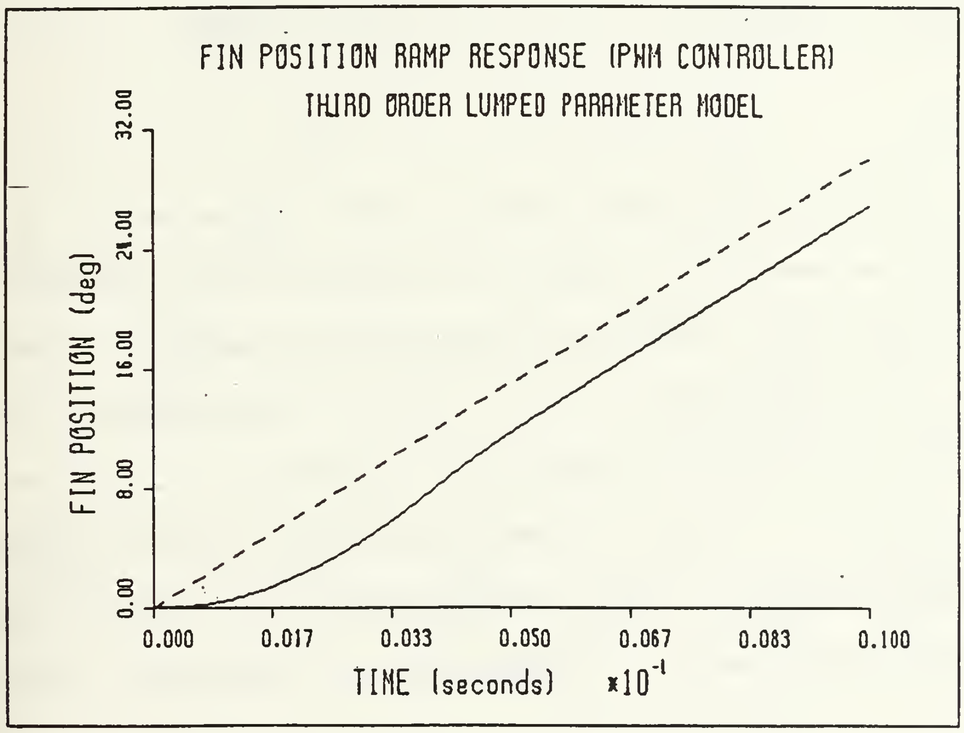


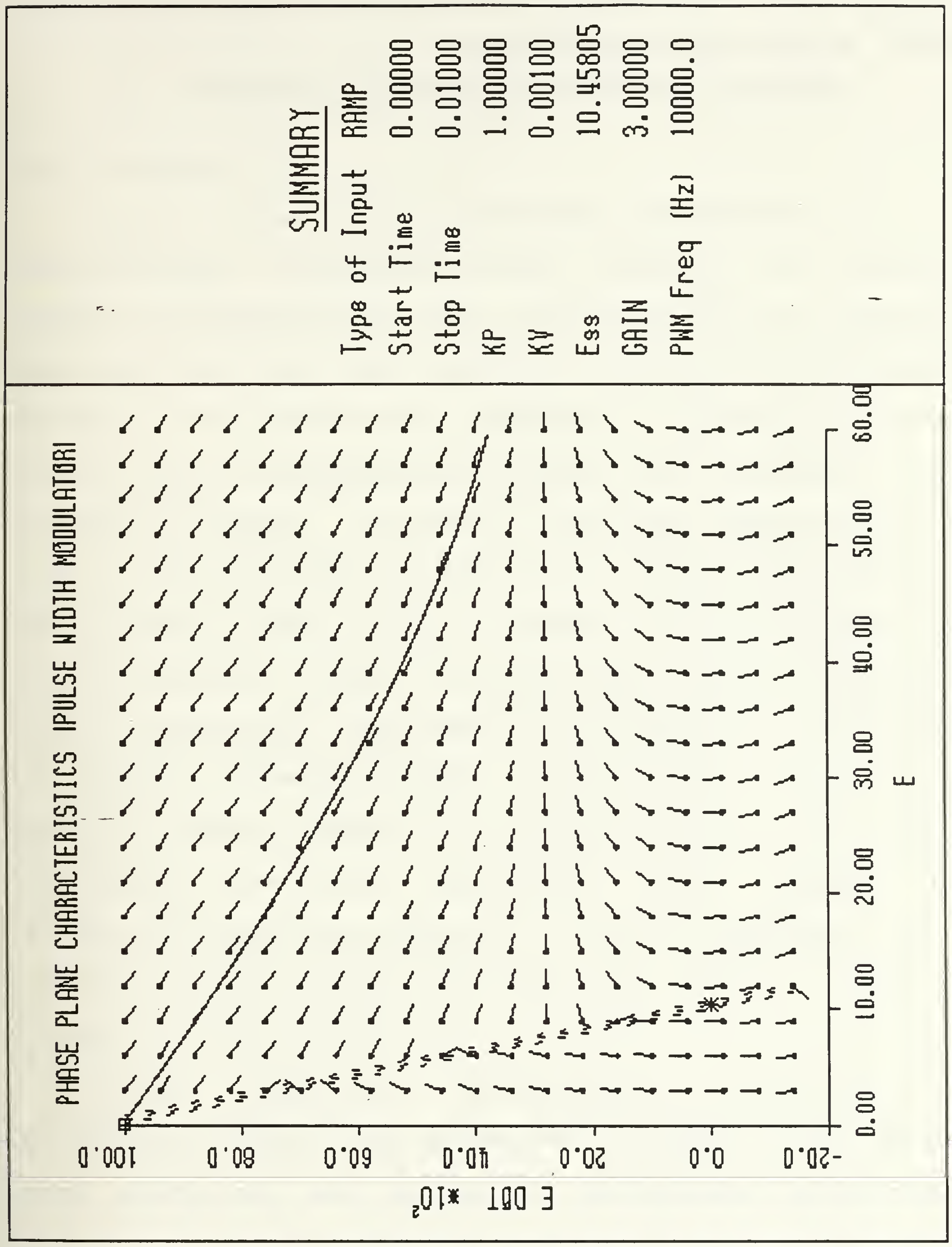
Figure 6.32 Third Order Model Fin Position Ramp Response

the second and third order lumped parameter models. Transient behavior is rapid and steady state tracking accuracy of this demanding input is tolerable.

Of particular interest is the phase plane representation of the system's dynamic limitations which describe the motor's torque capabilities. Figure 6.33 illustrates the case where the system's maximum position tracking rate precludes stable convergence when a ramp input of $\dot{r}$=10000 deg/sec is used. At steady state, the trajectory becomes asymptotic to the horizontal line given by Equation 6.24. Steady state error is infinite, indicating ramp response instability.

$$\dot{e}_{ss} = \dot{r} - \omega_{fss(O.L.)} = 10^4 - 7277 = 2623 \ \frac{\text{fin-deg}}{\text{sec}} \qquad (6.24)$$

The phase plane has been used extensively in this chapter as a method for gaining insight of the controller's dynamics and for selecting preliminary design parameters. However, two important final design considerations remain unaddressed and are the focus of attention in Chapter VII. Proper design of this electromechanical system requires compromise between system performance and reliability of electronic components. Additionally, thorough simulation



SUMMARY

Type of Input	RAMP
Start Time	0.00000
Stop Time	0.01000
KP	1.00000
KV	0.00100
Ess	10.45805
GAIN	3.00000
PWM Freq (Hz)	10000.0

Figure 6.33 Phase Plane / Unstable Ramp Response

of the final design must be accomplished using the detailed model of the brushless dc motor.

VII. PARAMETER OPTIMIZATION BY SIMULATION METHOD

A. BACKGROUND

Proper design of a position controller for an electronically commutated cruise missile fin actuator demands consideration of the system's mechanical response characteristics and the associated transient environment imposed on its solid state components. Preliminary design based solely on mechanical performance was presented in the preceeding chapter. Electrical transient behavior of the system was developed and studied in Chapters III and IV. The central theme of this chapter is investigation of electromechanical design considerations, where compromise between mechanical performance and electronic reliability is required. The application of pulse width modulation to position control, studied in Chapters V and VI, was shown to provide the broad performance range necessary to accomodate electrical-mechanical design compromises and, therefore, was selected as the means of fin actuation control for this design.

Design parameters independently determined in preceeding chapters are summarized in Table V and yield good electrical and mechanical performance properties.

These values serve as the starting point in the final design.

TABLE V

SUMMARY OF PRELIMINARY DESIGN PARAMETERS

PWM Amplifier Gain (K_{PWM})	3.0
PWM Pulsing Frequency (f_{PWM})	10KHz
PWM Controller Dead Zone (DBAND)	0.0°
Velocity Feedback Gain Coefficient (K_v)	0.001
Position Feedback Gain Coefficient (K_p)	1.0
Bias Threshold Voltage Divider %	50%
Commutation Offset (THADV)	0.0°
Plugging Delay (TDPLUG)	500 μsec
Decay Rate Resistance (RDADJ)	3 Ω

System performance design conducted in Chapter VI was based primarily on small scale step response analysis. Using a 3° fin perturbation, phase plane trajectories of the reduced order model were characterized by slightly underdamped behavior. No overshoot and very little transient oscillation were noted. A relatively large scale ramp response (3000°/sec) was also studied using the same design criteria, and was observed to behave very acceptably. The validity of this design based on lumped parameter modeling is initially ascertained through simulation using the detailed brushless dc motor model listed in Appendix A. Subsequent to fine adjustment of design parameters, large scale step, ramp, and sinusoidal response analyses are performed to determine the controller's robustness.

B. SIMULATION

Validation of the small scale step response analysis performed in the phase plane is readily accomplished through simulation using the detailed model listed in Appendix A. While small scale step analysis does not accurately represent the tracking dynamics encountered in missile flight control, it does provide a general and convenient standard for selection of controller design parameters.

1. Small Scale Step Response

Simulation using the preliminary design parameters summarized in Table V duplicate the system configuration selected in Chapter VI. In addition to system response verification, observation of the corresponding electrical transient behavior is afforded. Figures 7.1 through 7.4 illustrate the electromechanical performance of the

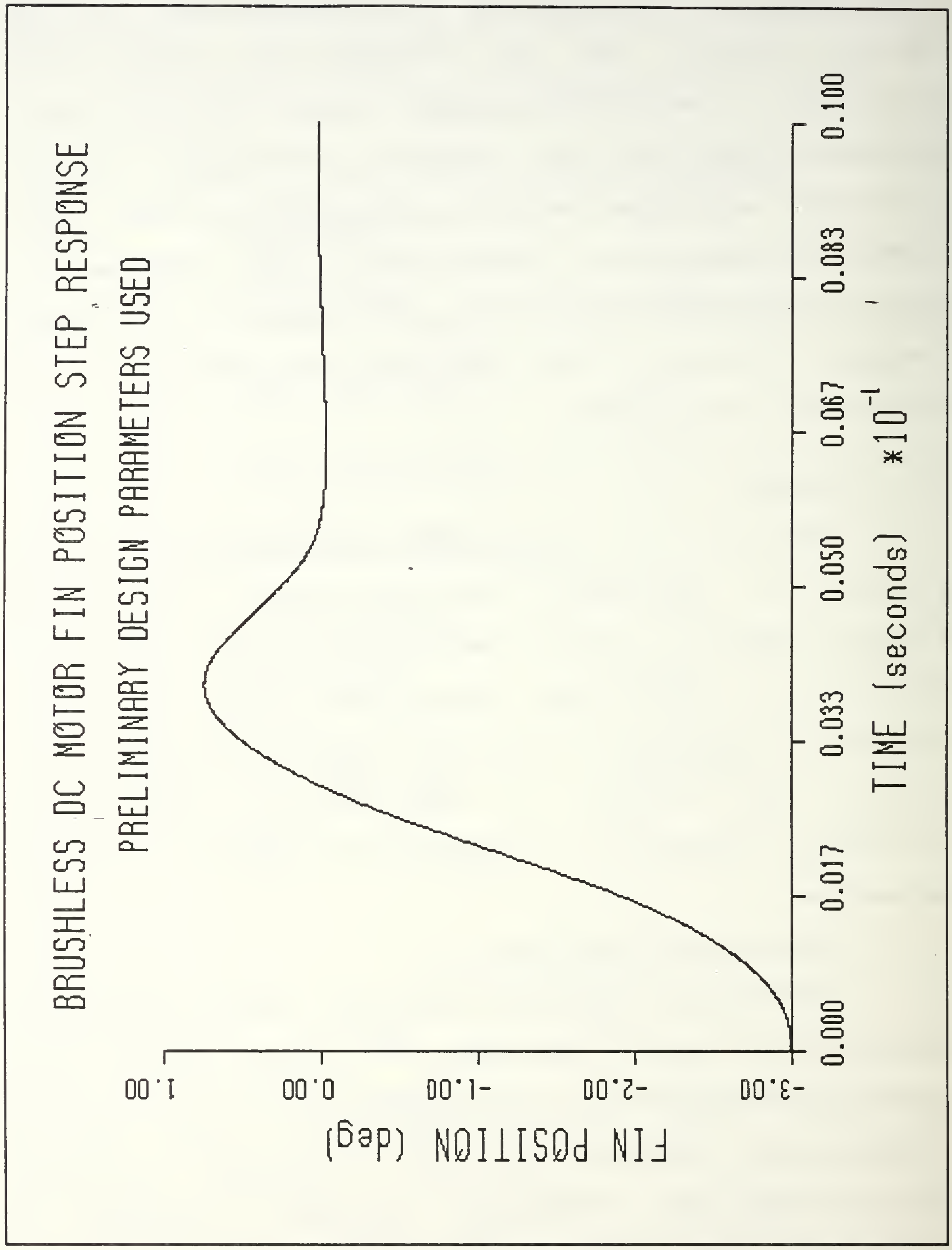


Figure 7.1 Fin Position Step Response (Preliminary Design)

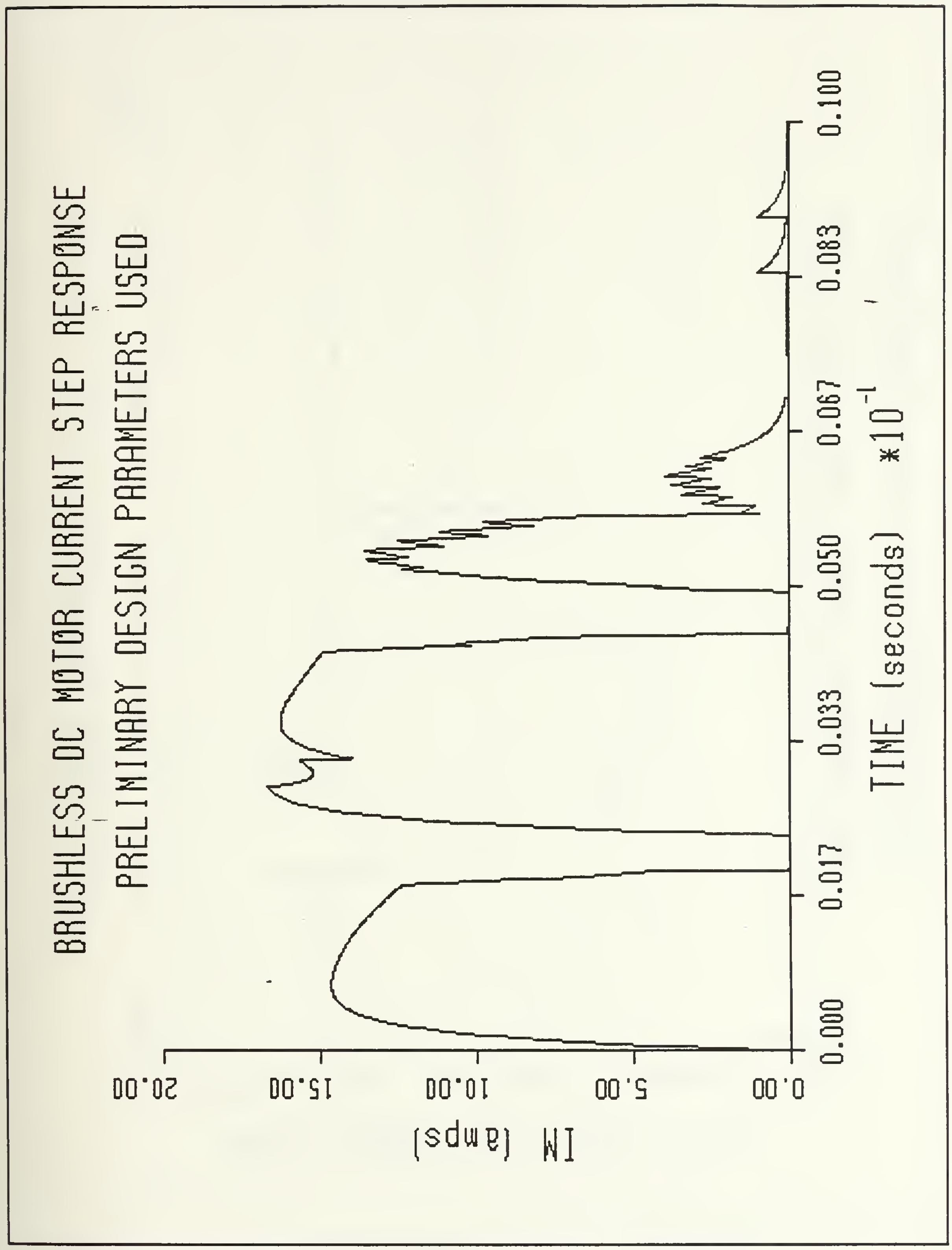


Figure 7.2 Motor Current Step Response (Preliminary Design)

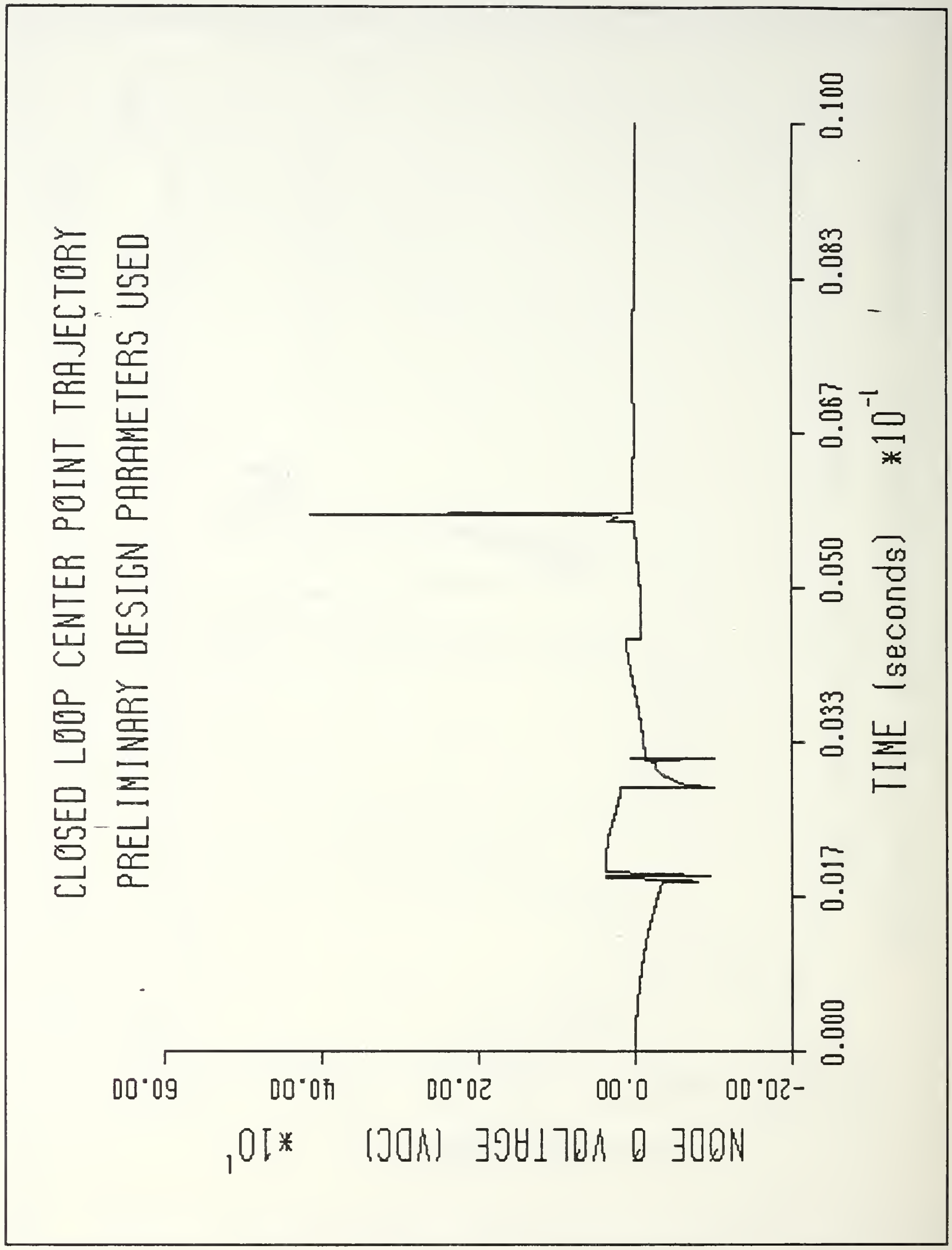


Figure 7.3 Node O Voltage Step Response(Preliminary Design)

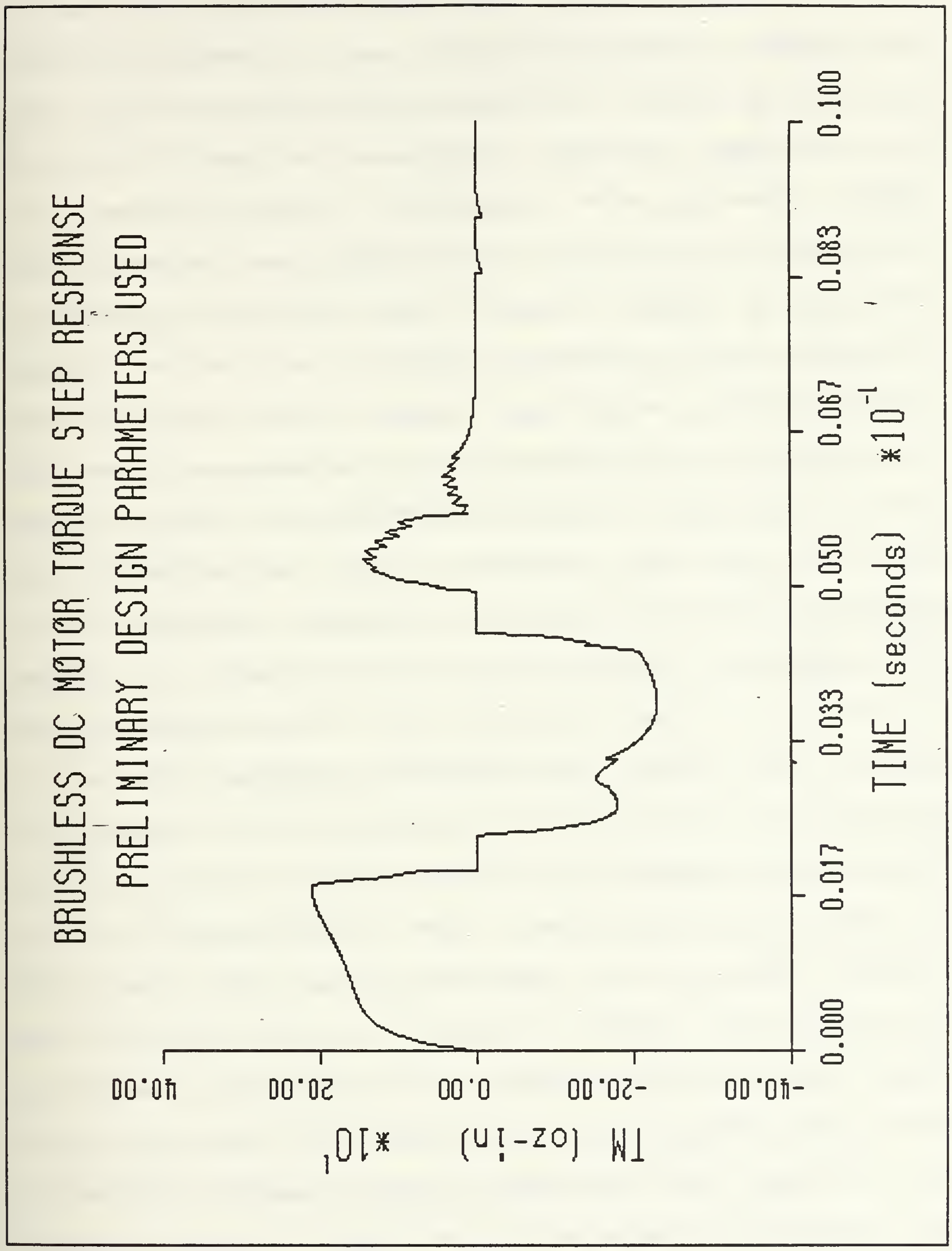


Figure 7.4 Motor Torque Step Response (Preliminary Design)

preliminary design when simulated with the brushless dc motor model. Figure 7.1 depicts the fin position response to a 3° step input. Of particular interest is the presence of a 25% peak overshoot, which was not predicted by the lumped parameter model simulation. Associated with the oscillatory transient are a relatively large current demand exhibited in Figure 7.2 and a 400 volt spike observed in the center point trajectory of Figure 7.3. Torque response characteristics are given in Figure 7.4 and vividly display the relatively long duration of natural response due to the use of a plugging delay time (TDPLUG) of 500μsec. System relaxation of such duration invites unacceptably large degrees of ballistic overshoot. However, plugging delay of some extent is required due to the inevitable requirement for current reversal associated with forced braking of the motor. The closed loop transient analysis performed in Chapter III assumes maximum stiffness in the controller's operation and employs the characteristics of an ideal relay to simulate such behavior. When maximum current flow is reversed, there is an understandable need for dissipation of excess coil energy. However, a soft controller was determined to be best suited in the preliminary design and pulse width modulation using an amplifier gain (K_{PWM}) of 3 was selected. The resulting buffering action provided by the controller eliminates the need for a lengthy current decay time during plugging. Figures 7.5 through 7.8

illustrate the small scale step response behavior using a reduced TDPLUG of 10 μsec. No overshoot is observed in the fin position step response shown in Figure 7.5 and system behavior is virtually identical with the results attained in lumped parameter modeling. Hence, the linear approximations required by phase plane design methods are validated and shown to be an effective means of predicting system performance. Figure 7.6 indicates substantial reduction in current demand when the plugging delay is decreased since system recovery from ballistic overshoot is not required. A peak voltage surge of only 100 volts is experienced at the center connection and is shown in Figure 7.7. Figure 7.8 illustrates the absence of any detectable period of natural motor torque response associated with plugging delay.

The erratic current response behavior illustrated in Figure 7.6 between .003 and .004 seconds is attributed to the periodic forcing nature of the PWM controller as the fin position settles. Near steady state conditions, the PWM pulse duty cycle is small and does not receive effective filtering by the system's electrical time constant. Therefore, the electrically developed torque shown in Figure 7.8 is also affected by the pulsation. It is observed, however, that the dominant mechanical low pass characteristics of the motor filters the oscillation and results in the smooth position response shown in

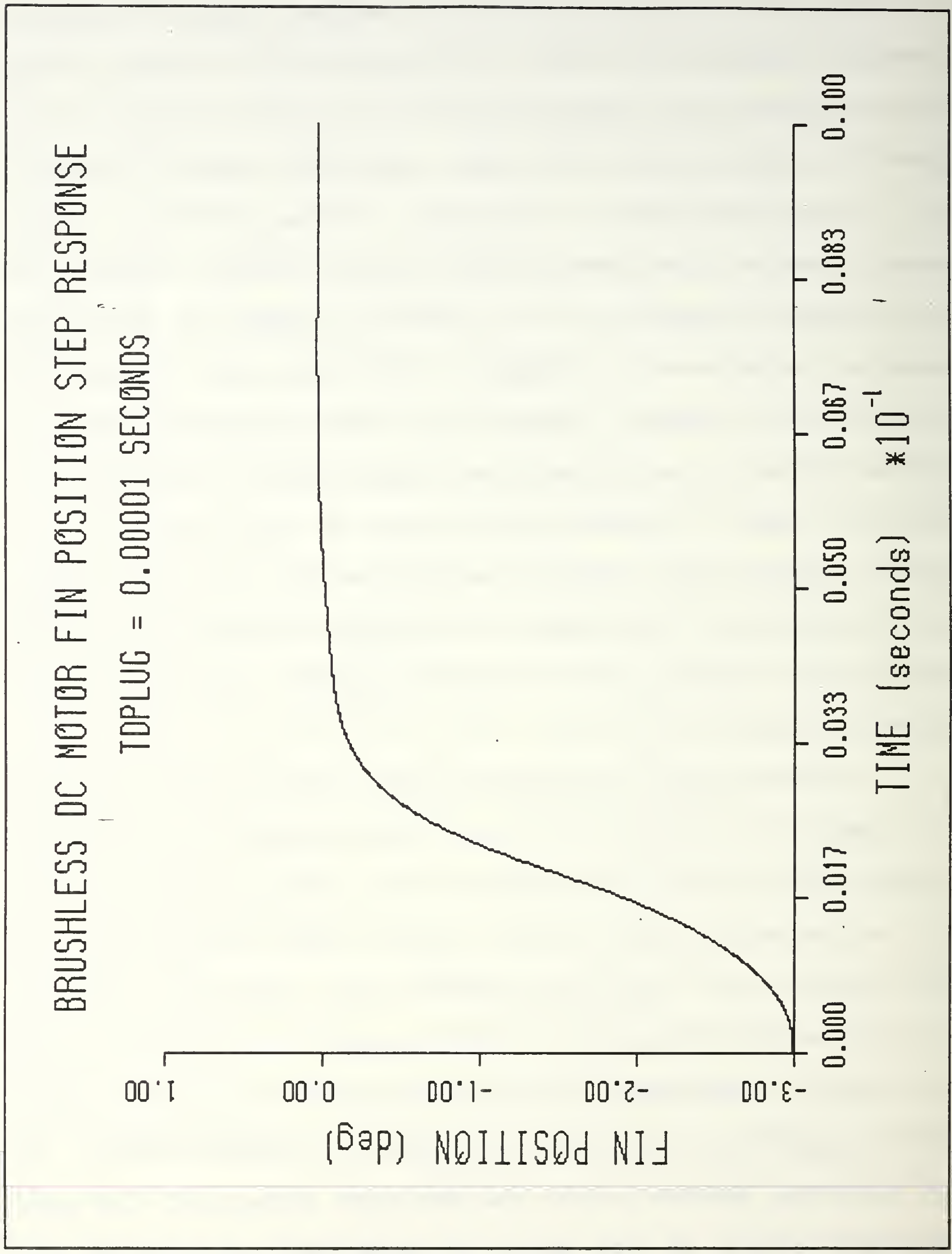


Figure 7.5 Fin Position Step Response (TDPLUG=10 μsec)

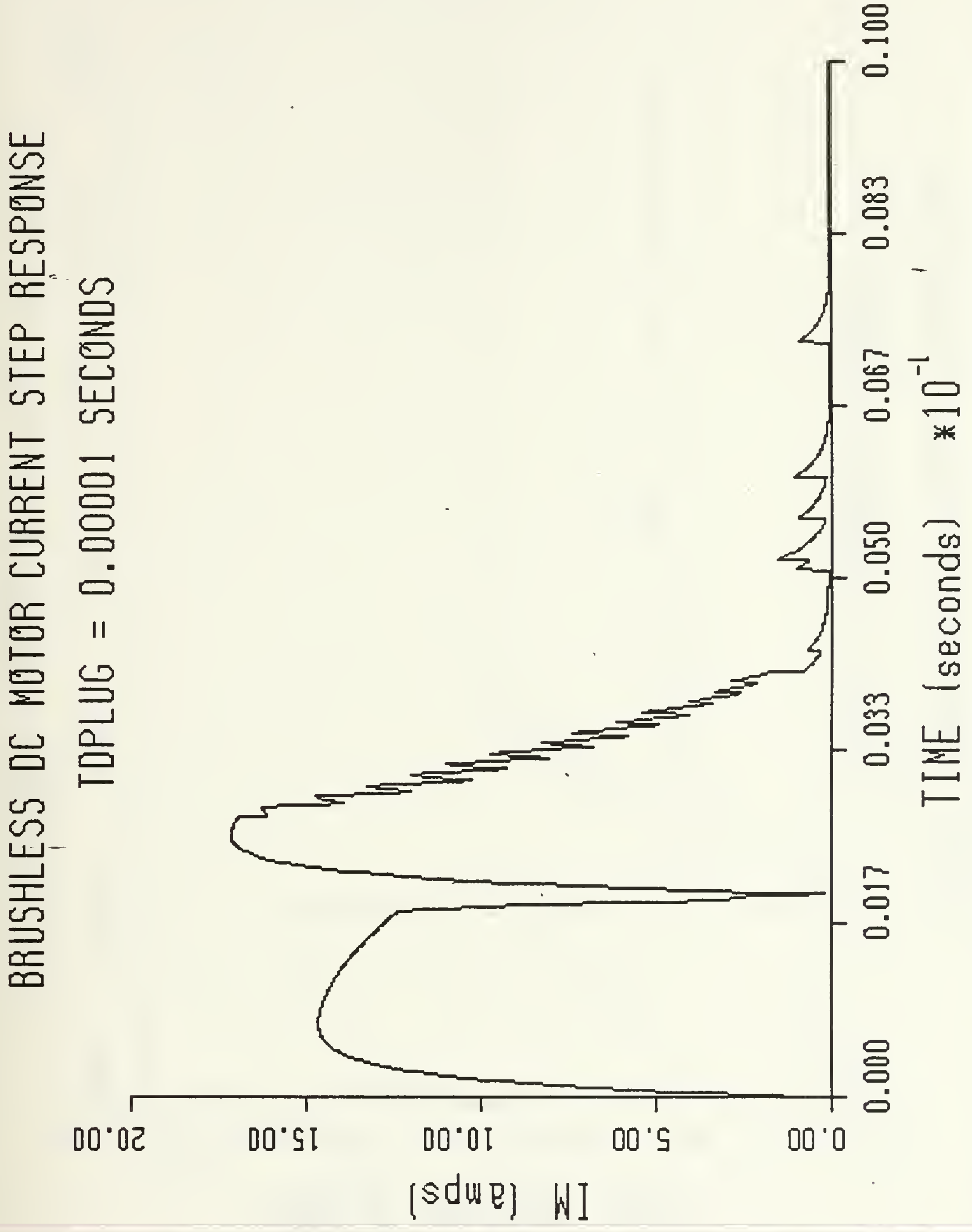


Figure 7.6 Motor Current Step Response (TDPLUG=10 μsec)

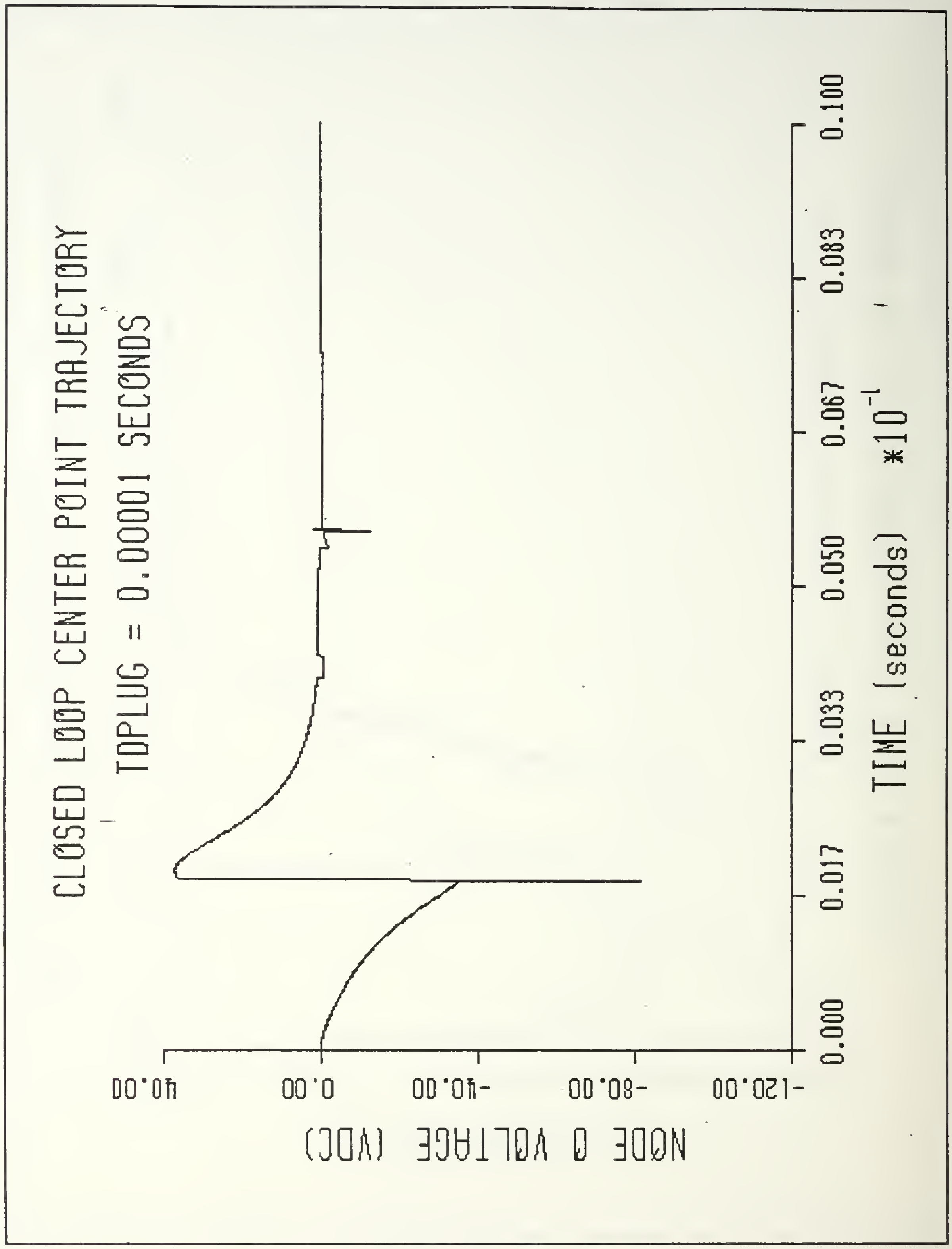


Figure 7.7 Node 0 Voltage Response (TDPLUG=10 μsec)

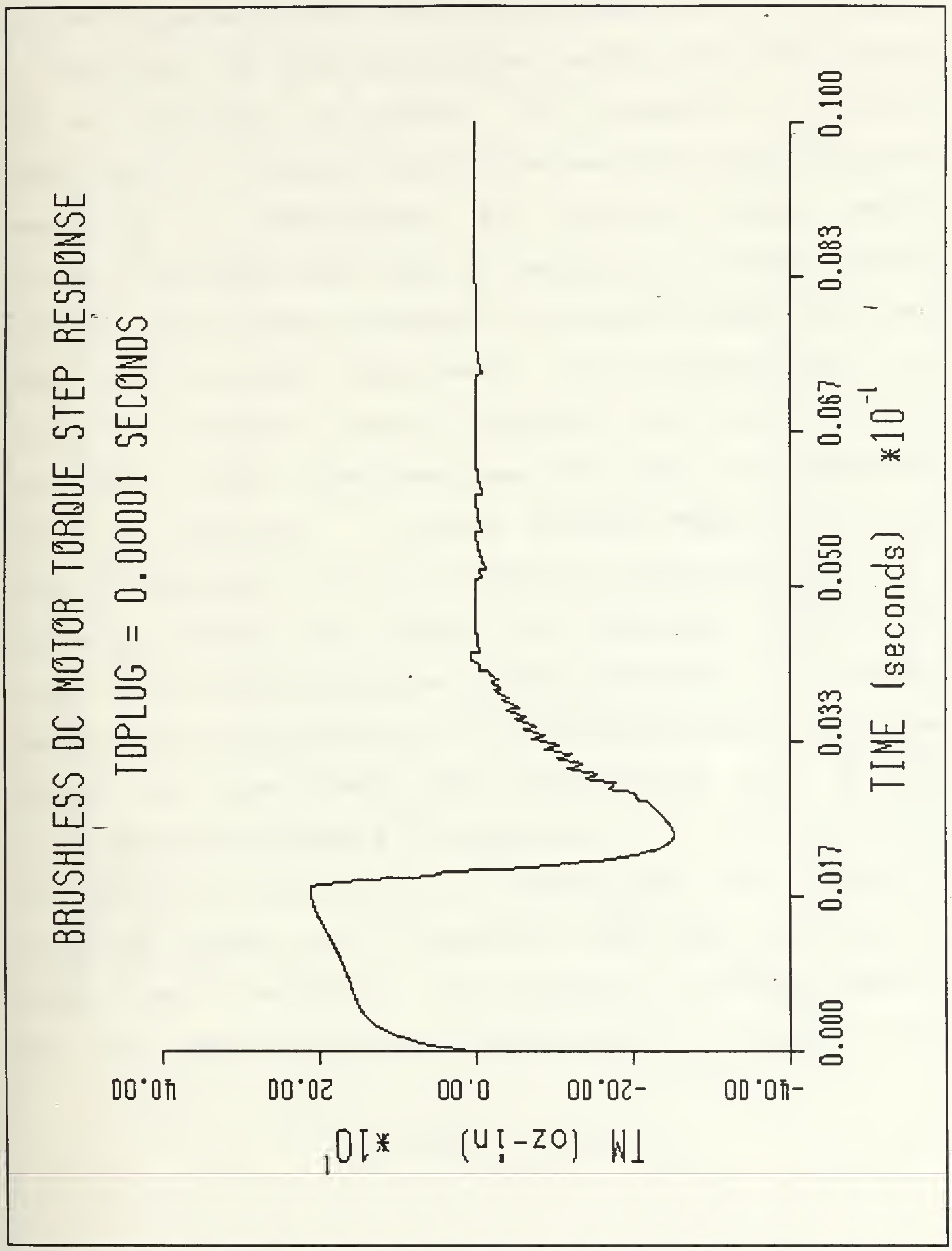


Figure 7.8 Motor Torque Step Response (TDPLUG=10 μsec)

Figure 7.5. The inclusion of a ±.5° dead zone decreases the extent of this forced oscillation and is described in Figures 7.9 through 7.11. Figure 7.9 portrays the fin position step response with the inclusion of dead zone. Steady state accuracy is compromised in a manner proportionate to the extent of dead zone employed. The fin position passes through its intended steady state position of 0° and settles at .5°. Once again, the relatively large region allowed for natural response supports ballistic overshoot of the fin position and causes additional undesired forced braking action. Because the motor undergoes commutation switching at 0°, the commutation logic is reverse sequenced and results in current reversal. Figure 7.10 indicates reduced susceptibility of the motor current to the pulsing action of the PWM due to dead zone, but is also characterized by rapid decay of current associated with the interaction of plugging and commutation switching. The rapid change in current flow is responsible for the 180 volt spike observed in the center connection voltage response of Figure 7.11. Analysis of small scale step response indicates that inclusion of dead zone not

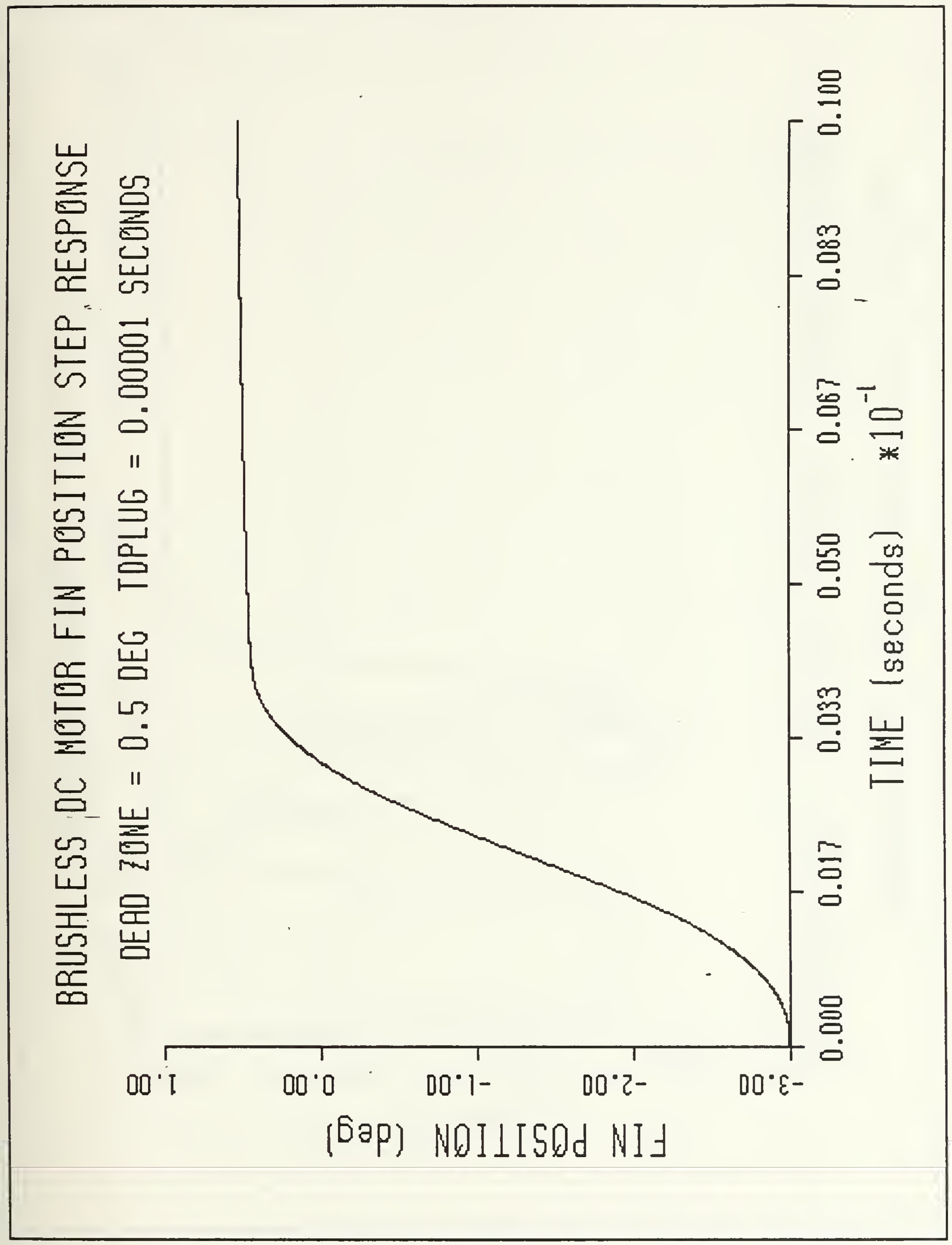


Figure 7.9 Fin Position Step Response (Dead Zone = ±.5°)

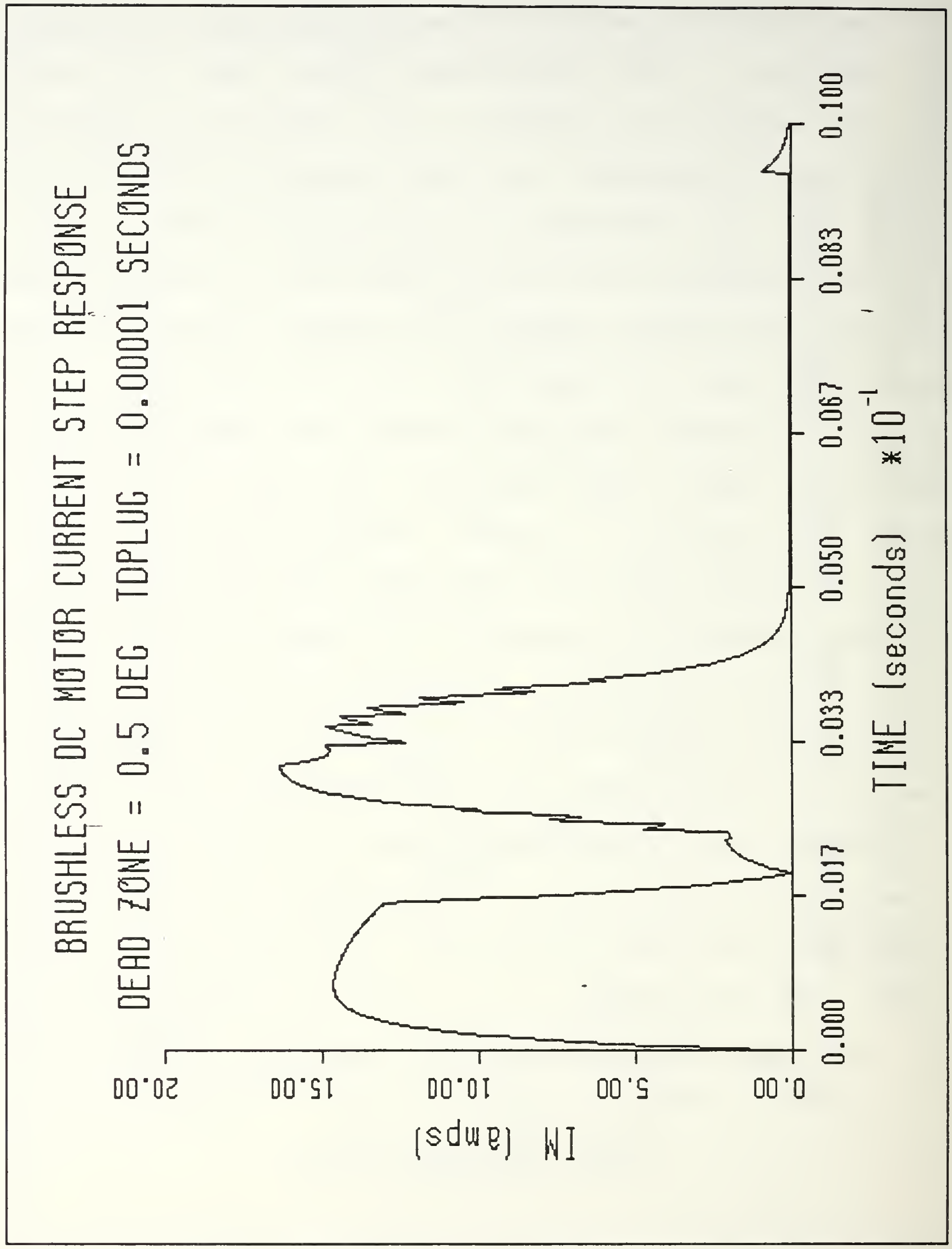


Figure 7.10 Motor Current Step Response (Dead Zone = ±.5°)

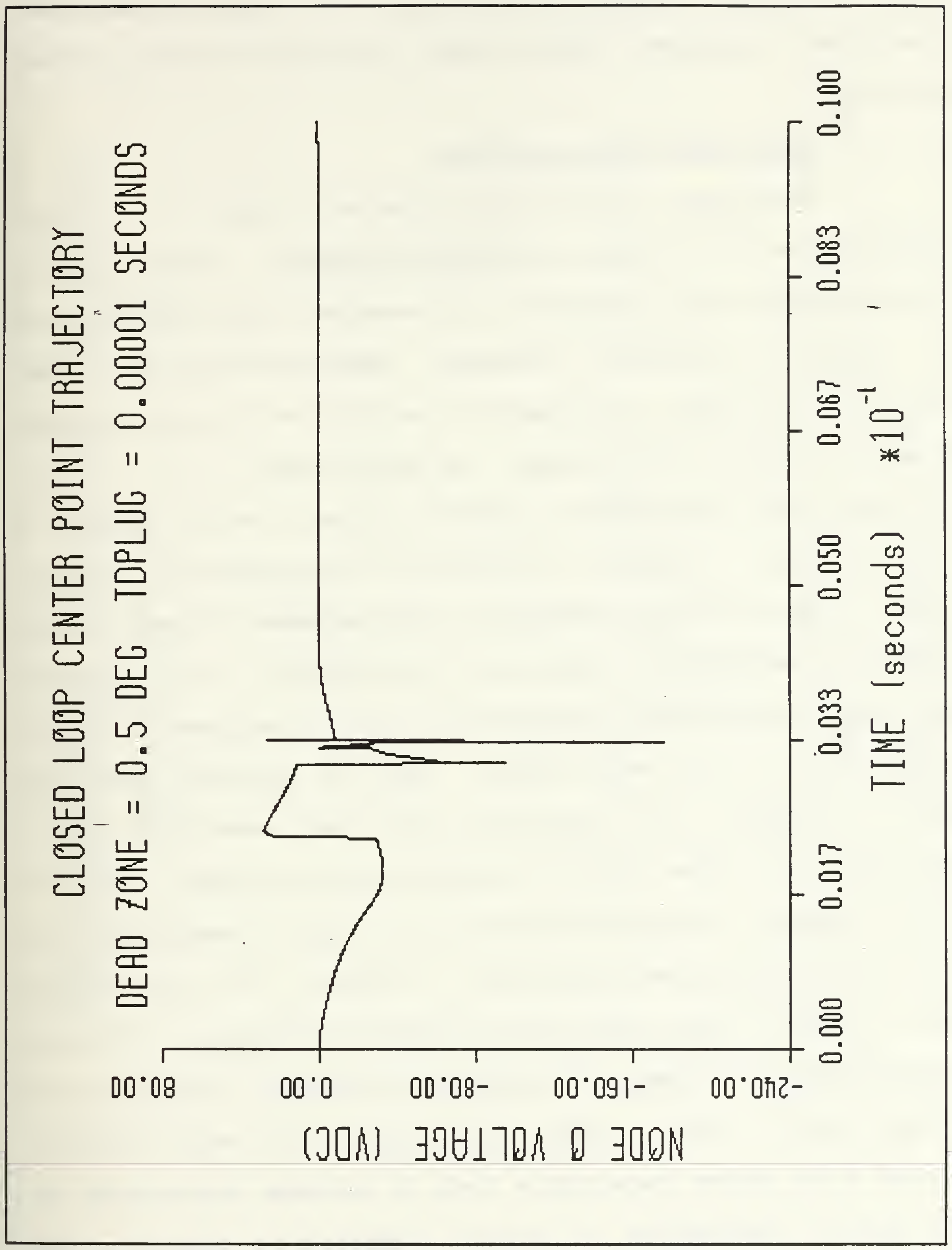


Figure 7.11 Node O Voltage Response (Dead Zone = ±.5°)

only degrades system accuracy, but also accentuates electrical transients due to the increased need for forced braking.

2. Large Scale Step Response

Stability of nonlinear systems often is largely dependent on the initial conditions imposed. Simulation of a large scale step response, for example, might be expected to display different response characteristics of the brushless dc motor fin position controller than have been observed using a small step. In application, it is highly unlikely that the missile command guidance would command a 45° fin step. However, because of its excessive nature, such a simulation was conducted for purposes of evaluating benchmark performance. Figures 7.12 through 7.14 illustrate the electromechanical performance of the brushless dc motor subjected to a 45° step input. The fin position response shown in Figure 7.12 indicates a 15% peak overshoot and a comparatively large settling time of 0.02 seconds. Both of these response characteristics are highly acceptable and indicate performance robustness. Figure 7.13 illustrates motor current large scale step response behavior. Although average current demand is relatively high due to the nature of the input, the current response is very well behaved. Figure 7.14 shows reasonable Node 0 voltage transients in the motor, indicative of proper commutation operation of

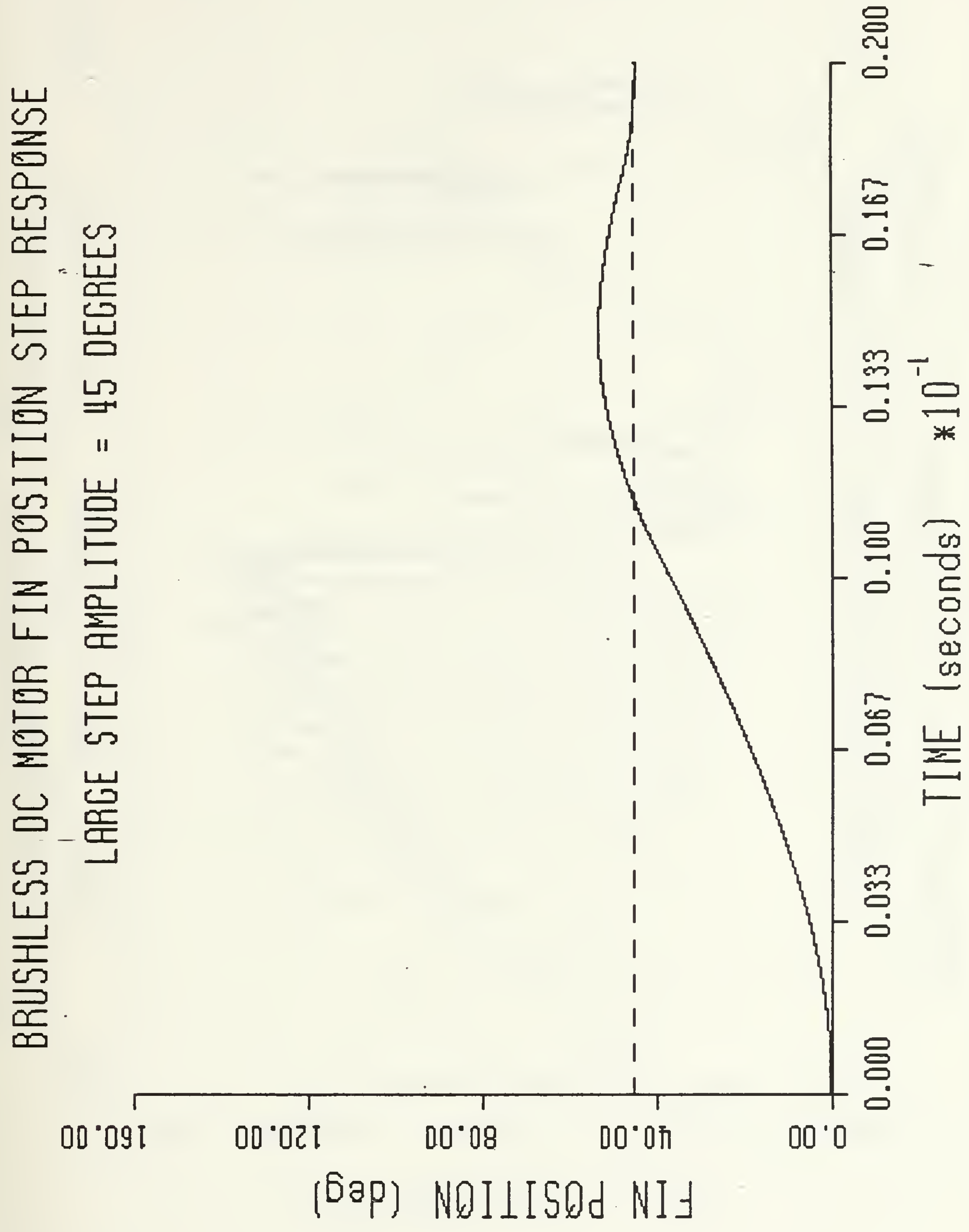


Figure 7.12 Fin Position Large Scale Step Response

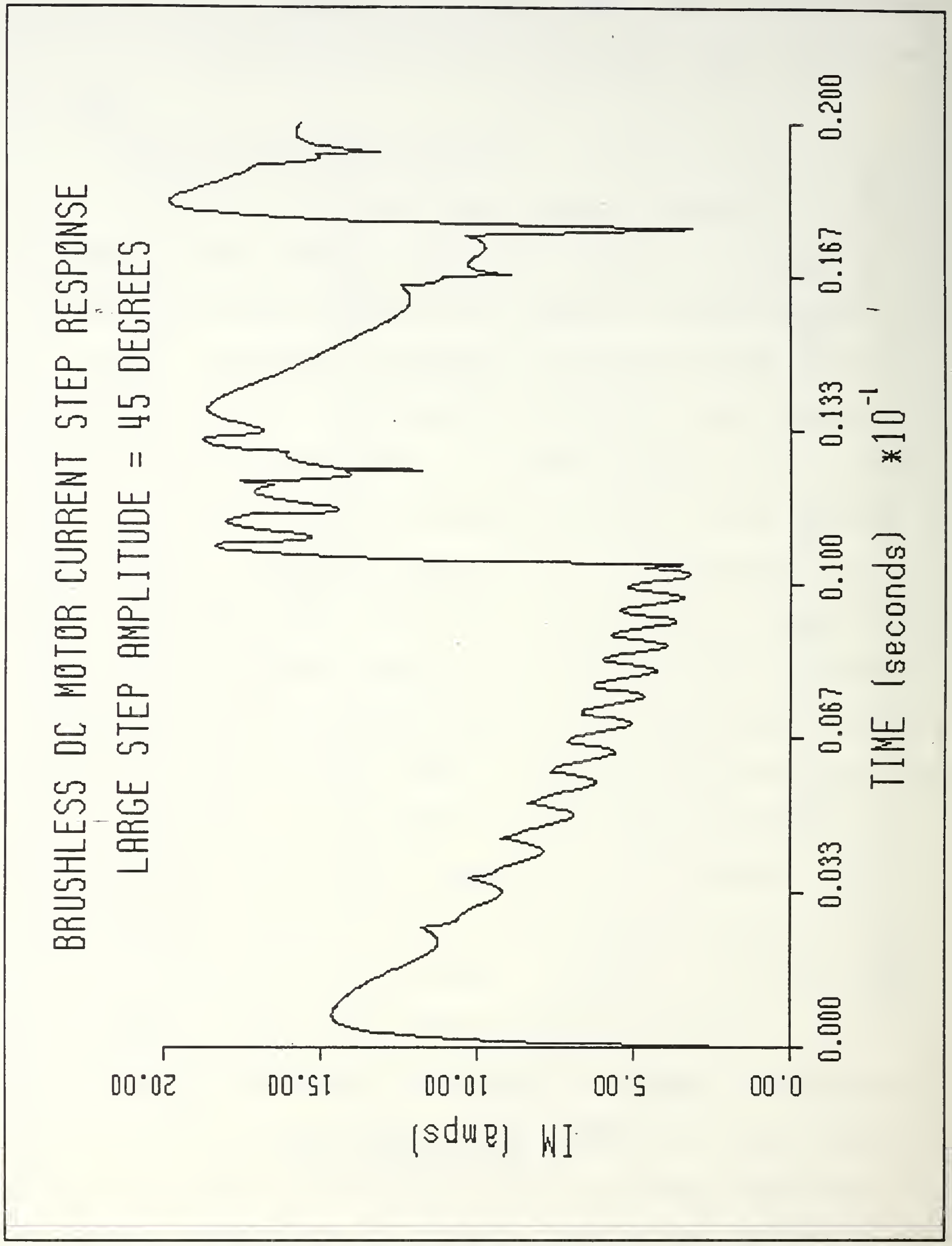


Figure 7.13 Motor Current Large Scale Step Response

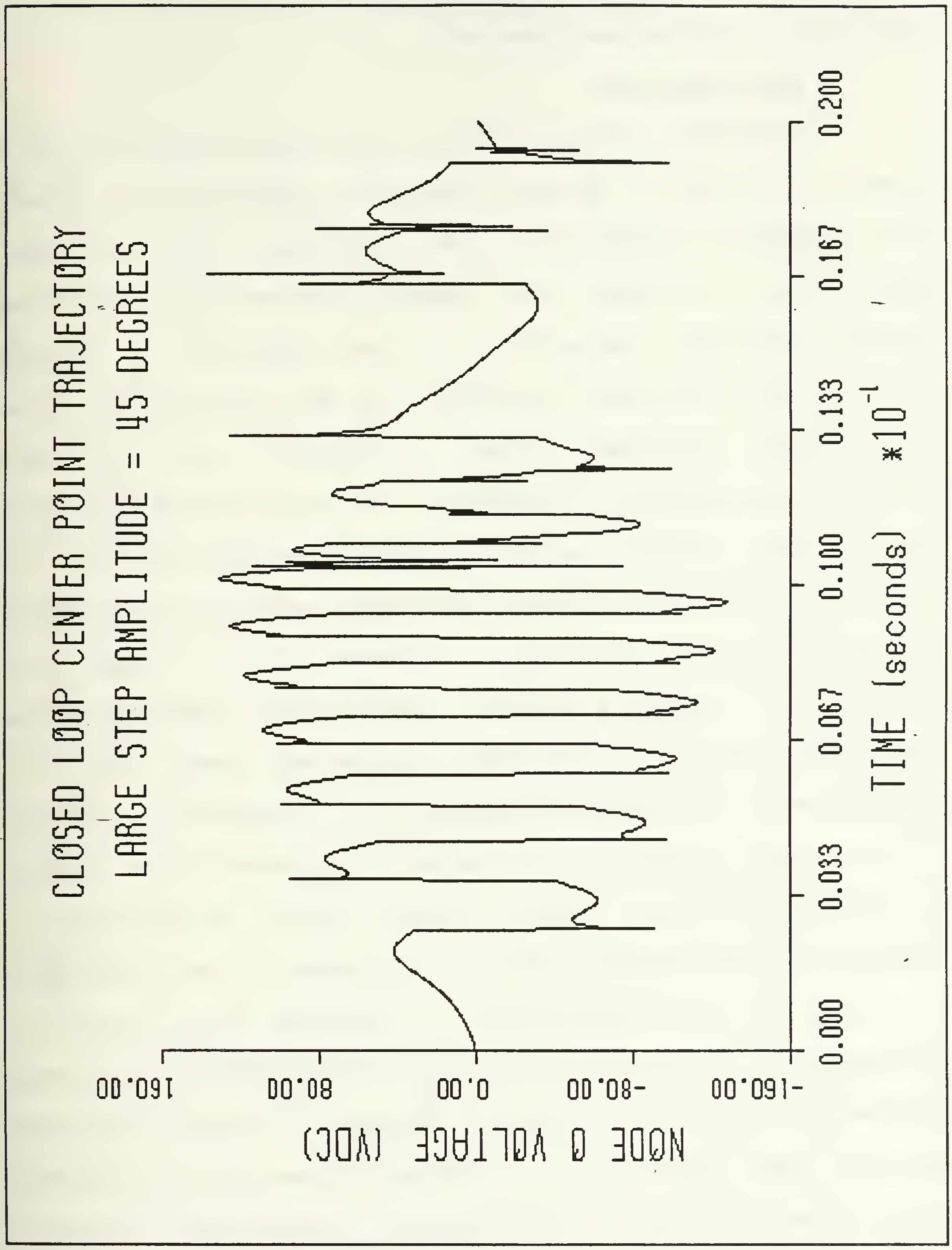


Figure 7.14 Node O Voltage Large Scale Step Response

the power conditioner. A maximum center connection voltage surge of 120 volts was observed.

3. Ramp Response

Since the cruise missile fin actuator behaves as a tracking device, a dynamic range of input values permit more realistic analysis of the controller. A stiff ramp input signal of slope 3000 deg/sec is used to attain the dynamic response behavior of the actuator. Similar analysis was previously conducted in the phase plane using the lumped parameter model. Although ramp response analysis specifically evaluates the positioning device's ability to perform as a constant velocity device, it provides rudimentary dynamic response behavior unavailable in step response analysis. Figures 7.15 through 7.19 display the tracker's dynamic performance characteristics simulated using a relatively demanding ramp input of 3000deg/sec. Tracking performance is illustrated in Figure 7.15 and very similar to the behavior observed using lumped parameter modeling. Steady state error, as defined in Chapter VI, is observed and is considered to be acceptable for this design application. Although the system is underdamped, transient oscillation is negligible and forced braking is kept to a minimum. Figure 7.16 gives the motor current ramp response and is characterized by a relatively high current demand. Additionally, significant harmonic

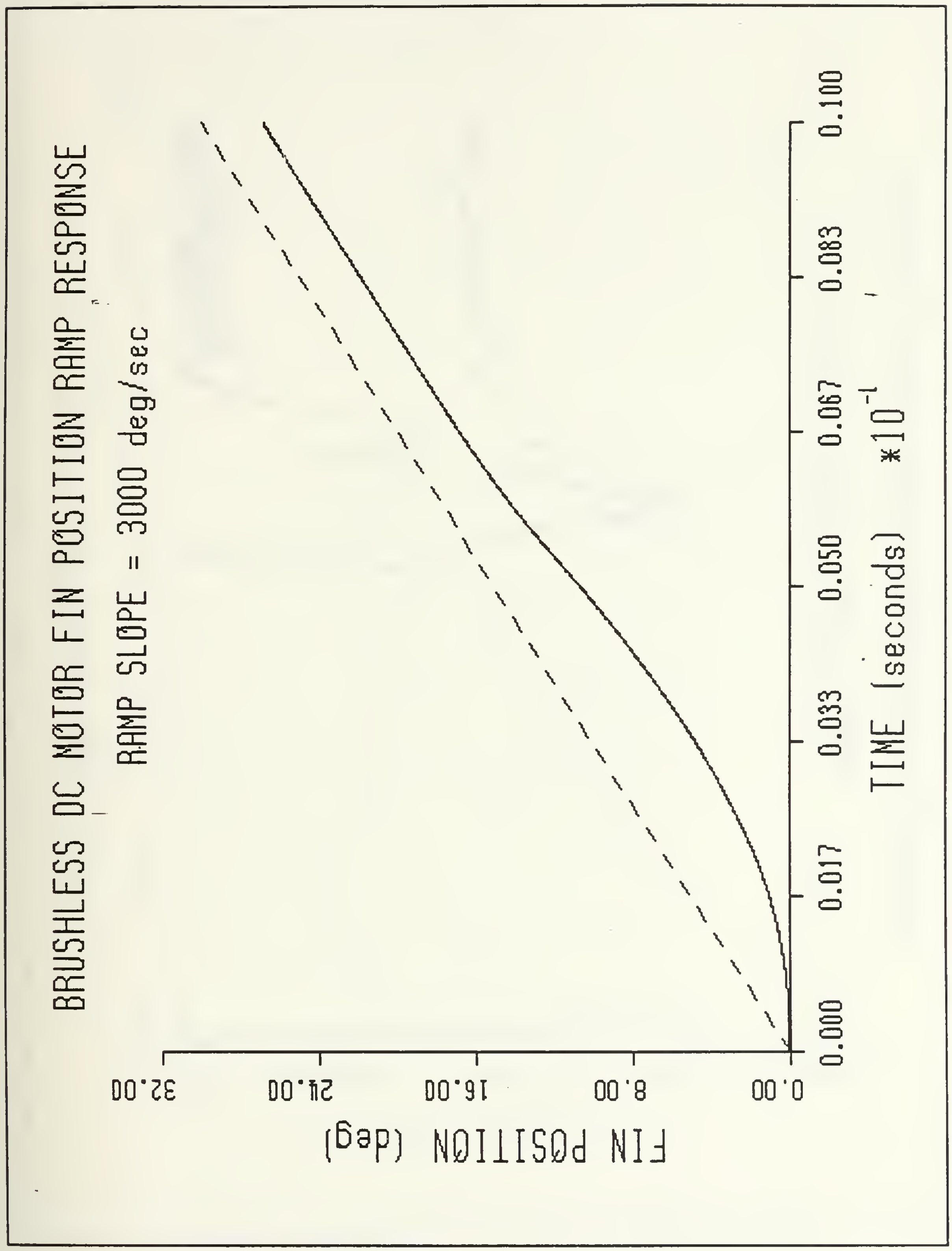


Figure 7.15 Fin Position Ramp Response

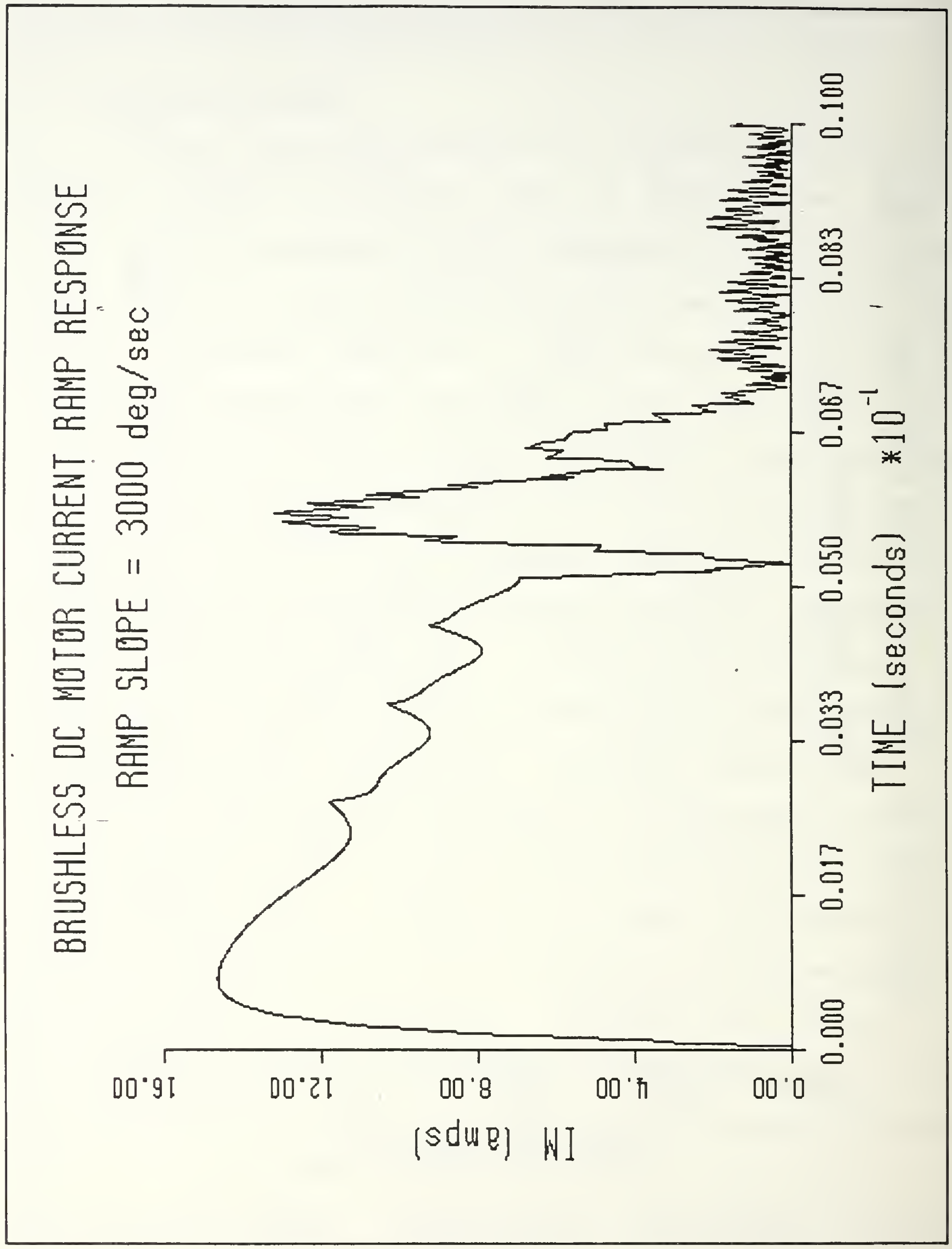


Figure 7.16 Motor Current Ramp Response

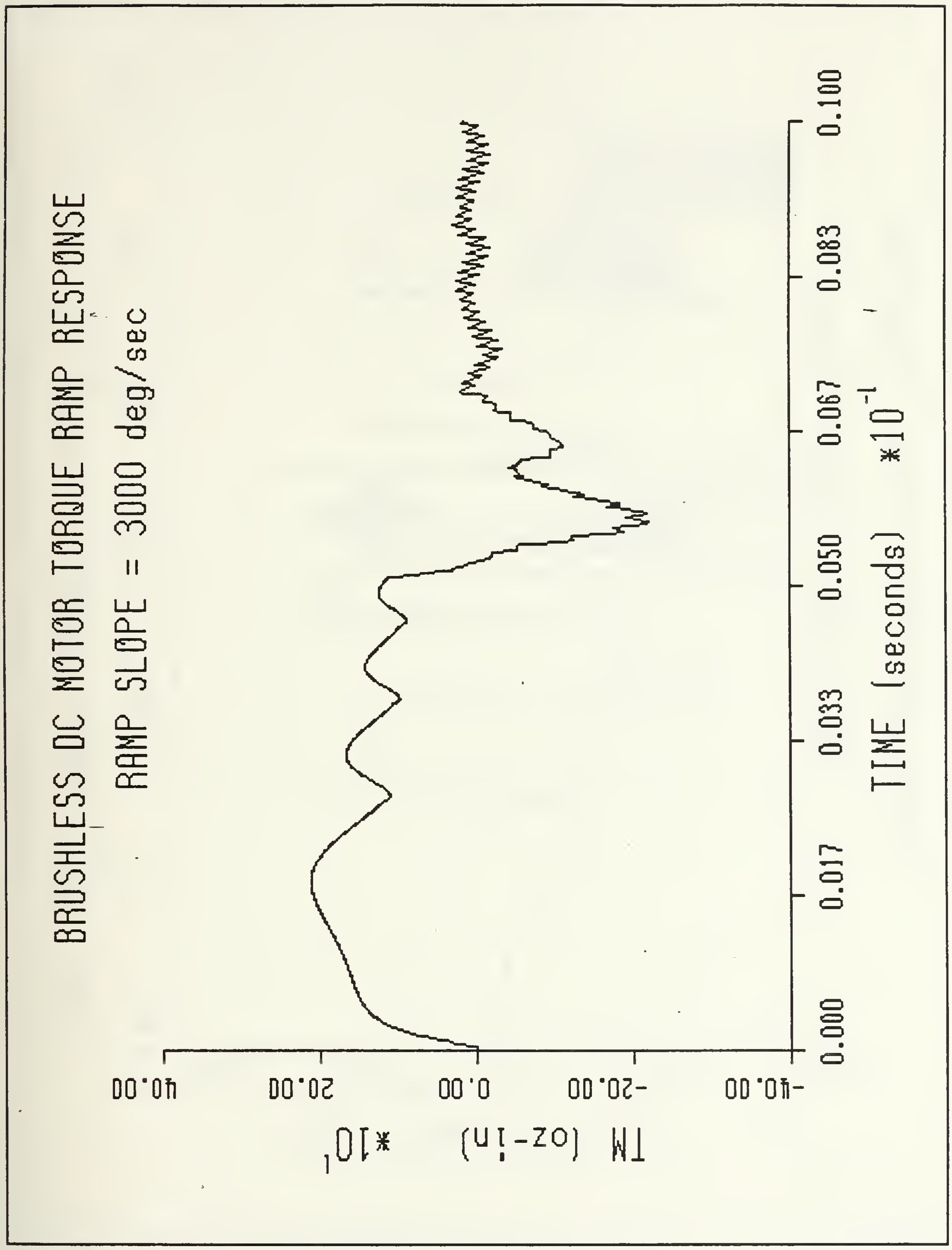


Figure 7.17 Motor Torque Ramp Response

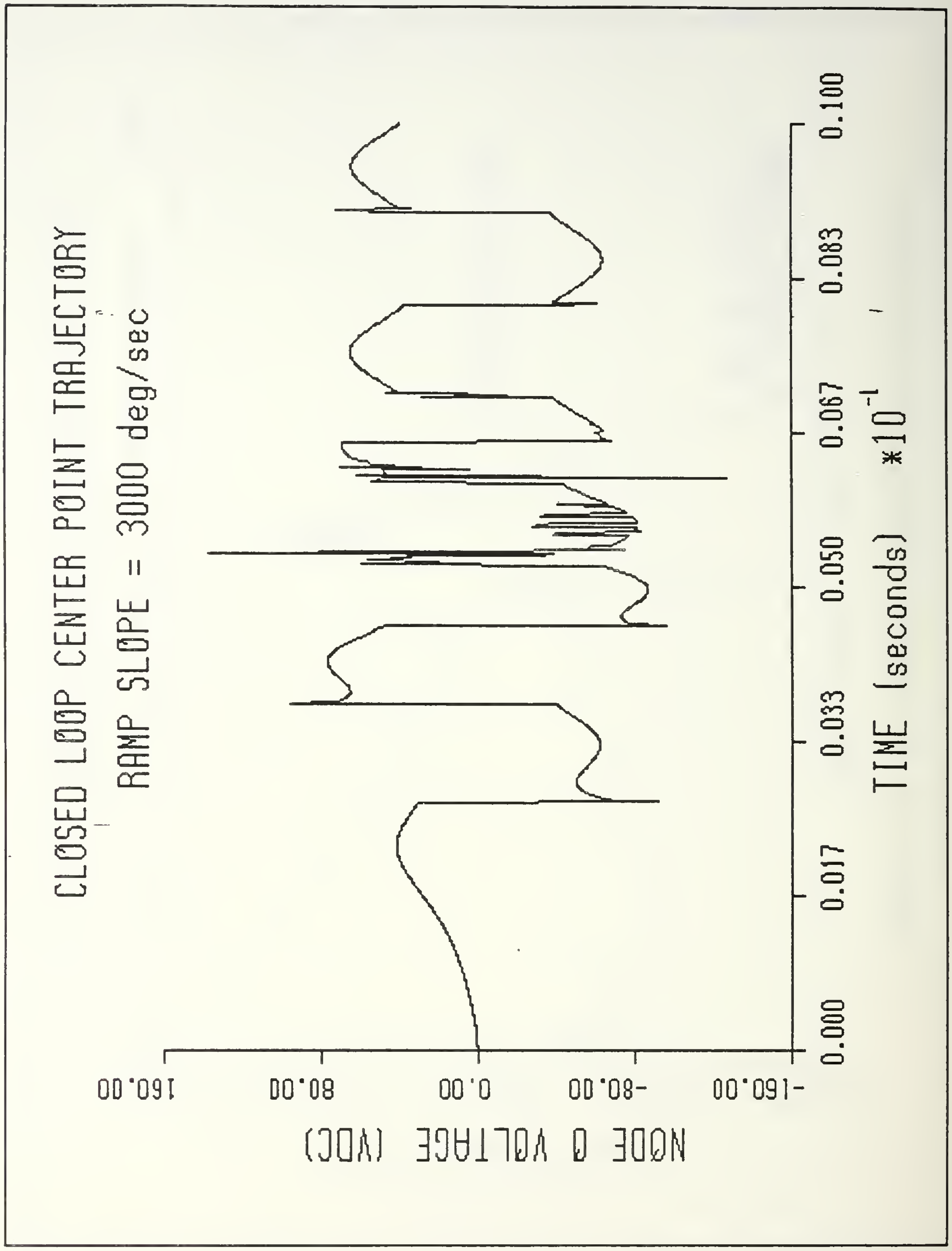


Figure 7.18 Node O Voltage Ramp Response

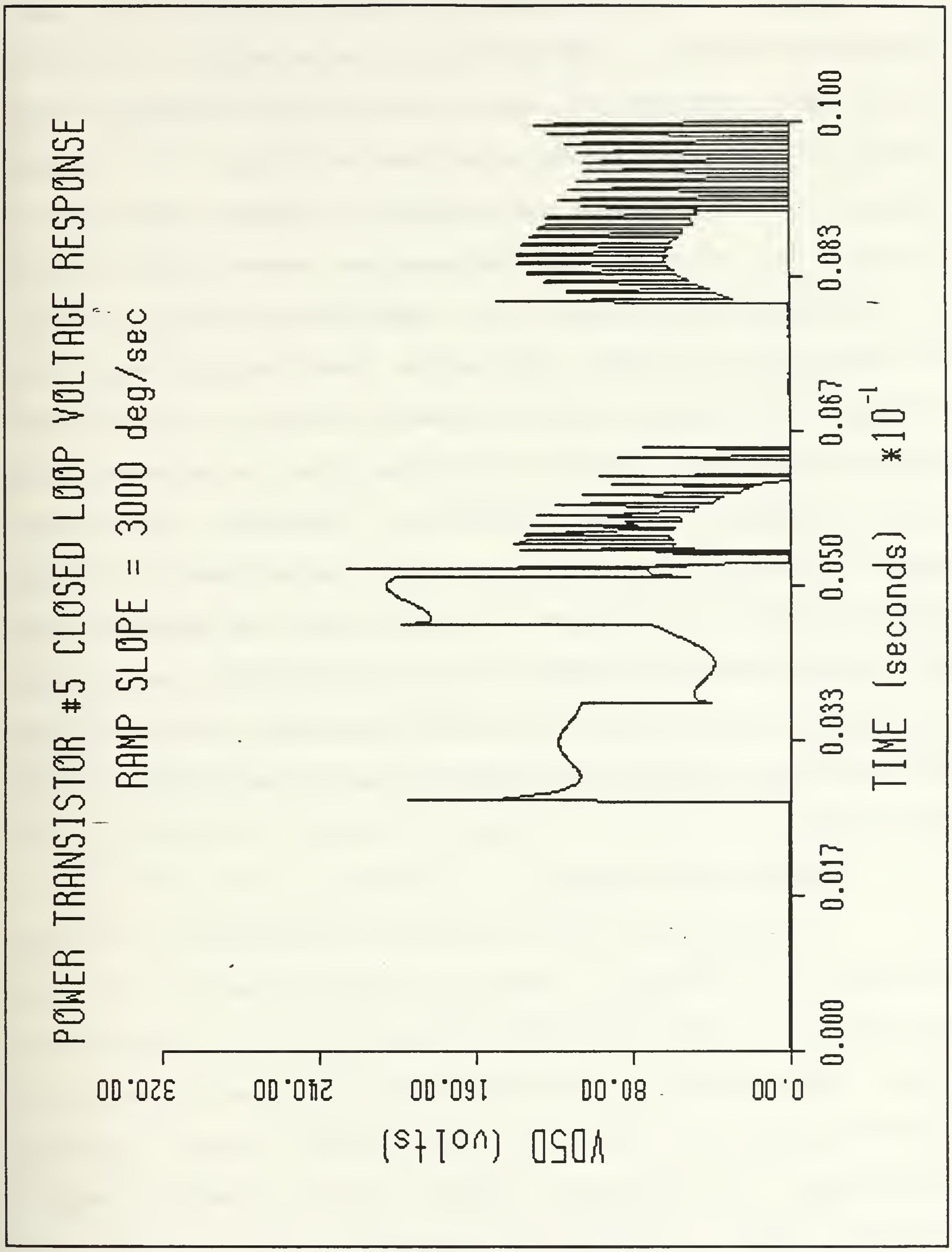


Figure 7.19 Transistor #5 Voltage Ramp Response

oscillation caused by PWM pulsing is exhibited near constant velocity. PWM pulsing is more clearly shown in the torque response of Figure 7.17, where transient and steady state oscillation also are exhibited. A center connection peak voltage surge of 150 volts is observed in Figure 7.18. The voltage response of Power Transistor #5 is illustrated in Figure 7.19. The pulsing effects of the PWM operating at low duty cycle near steady state are readily observed as moderate spiking across the transistor. Although this ragged forced response could be smoothed with use of higher pulsing frequencies, hardware constraints preclude such implementation. The corresponding voltage responses shown in Figures 7.18 and 7.19 are characterized by high frequency voltage transients of moderate magnitude. Therefore, despite the undesirable pulsing effects of the PWM, the ramp response characteristics are determined to be acceptable.

4. Sinusoidal Response

The final and most realistic simulation performed evaluates the dynamic tracking performance of the fin actuator by subjecting the controller to a sinusoidal input. The ability of the controller to track sinusoidally varying position commands demonstrates true tracking robustness. To simulate typical cruise missile command guidance flight correction commands, a sine wave of amplitude 3° and frequency of 100Hz was used as a reference input. Figures 7.20 through 7.23 illustrate electromechanical sine wave response characteristics of the fin actuator. Good tracking characteristics are exhibited in the fin position response of Figure 7.20. Although steady state error varies with the instantaneous slope of the input, it is acceptably small and is approximated at .3° at the sine's point of inflection. Figure 7.21 gives the motor current sine wave response and indicates considerable pulsing activity at near steady state conditions. These pulses are realized as voltage spikes at solid state components and the representative conditions at power transistor #5 are illustrated in Figure 7.22. However, the spikes are sufficiently small (170 volts) so as not to degrade solid state reliability. Figure 7.23 shows the center point trajectory when the controller is subjected to small amplitude sinusoidal inputs. A peak voltage surge of 15 volts is highly acceptable.

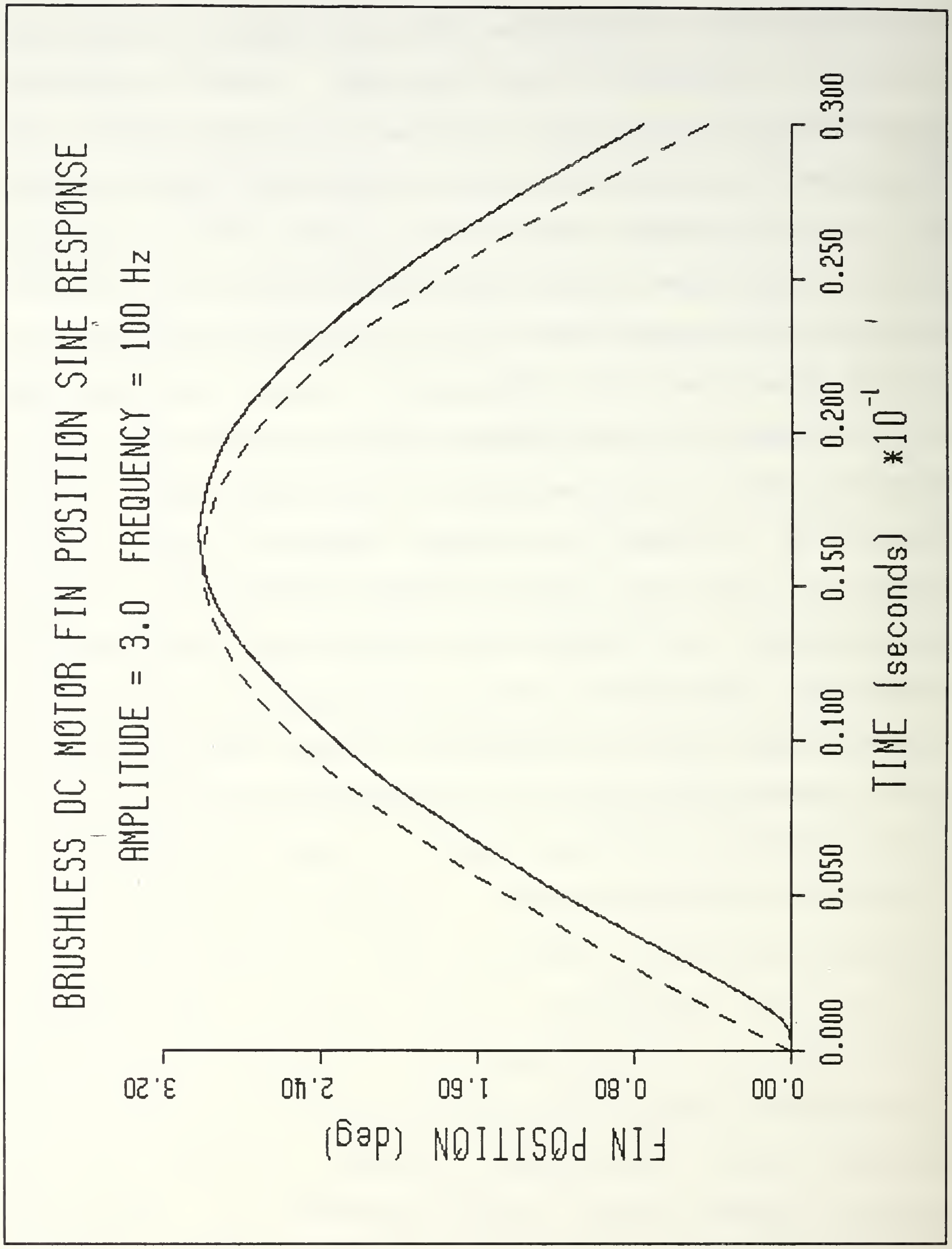


Figure 7.20 Fin Position Sinusoidal Response

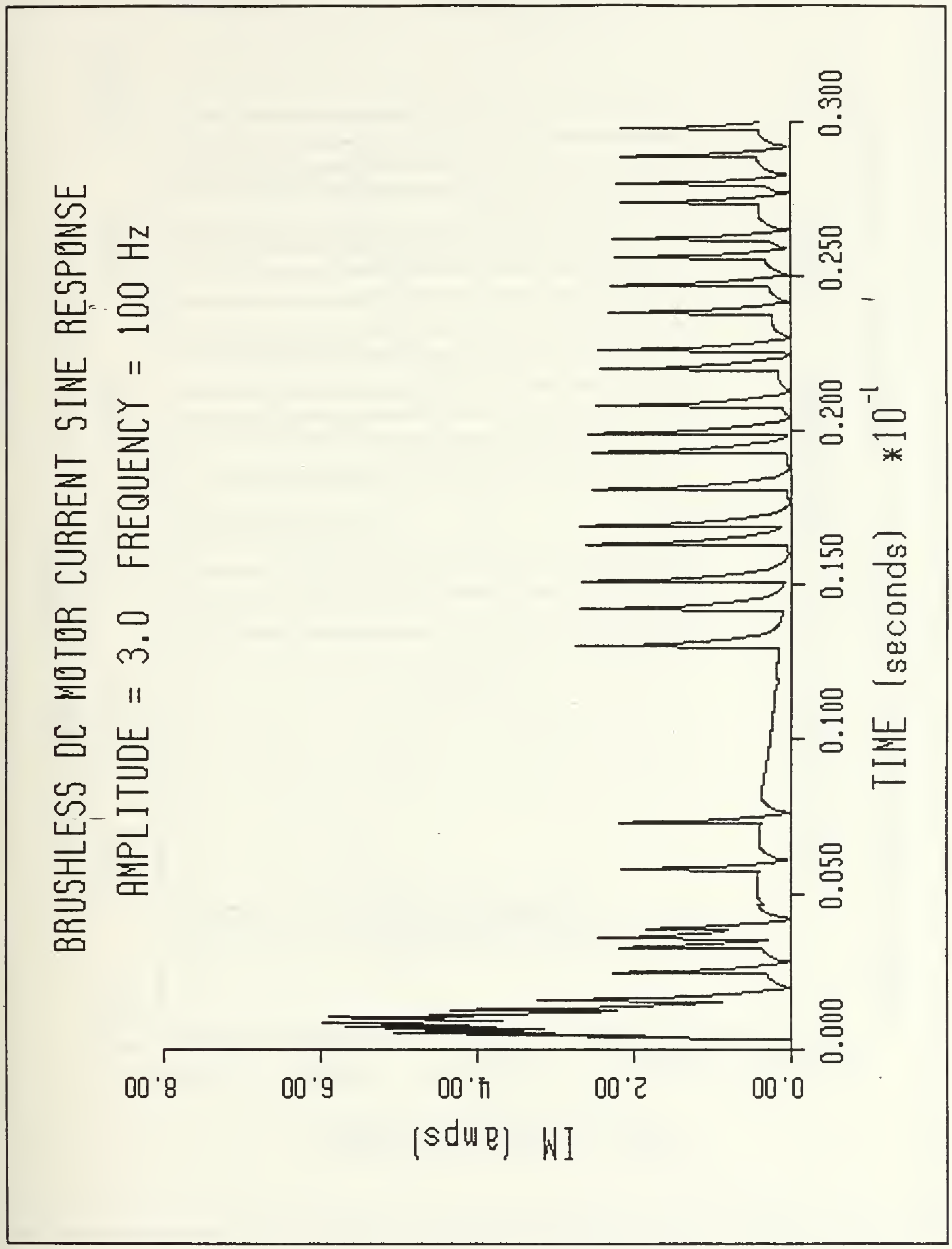


Figure 7.21 Motor Current Sinusoidal Response

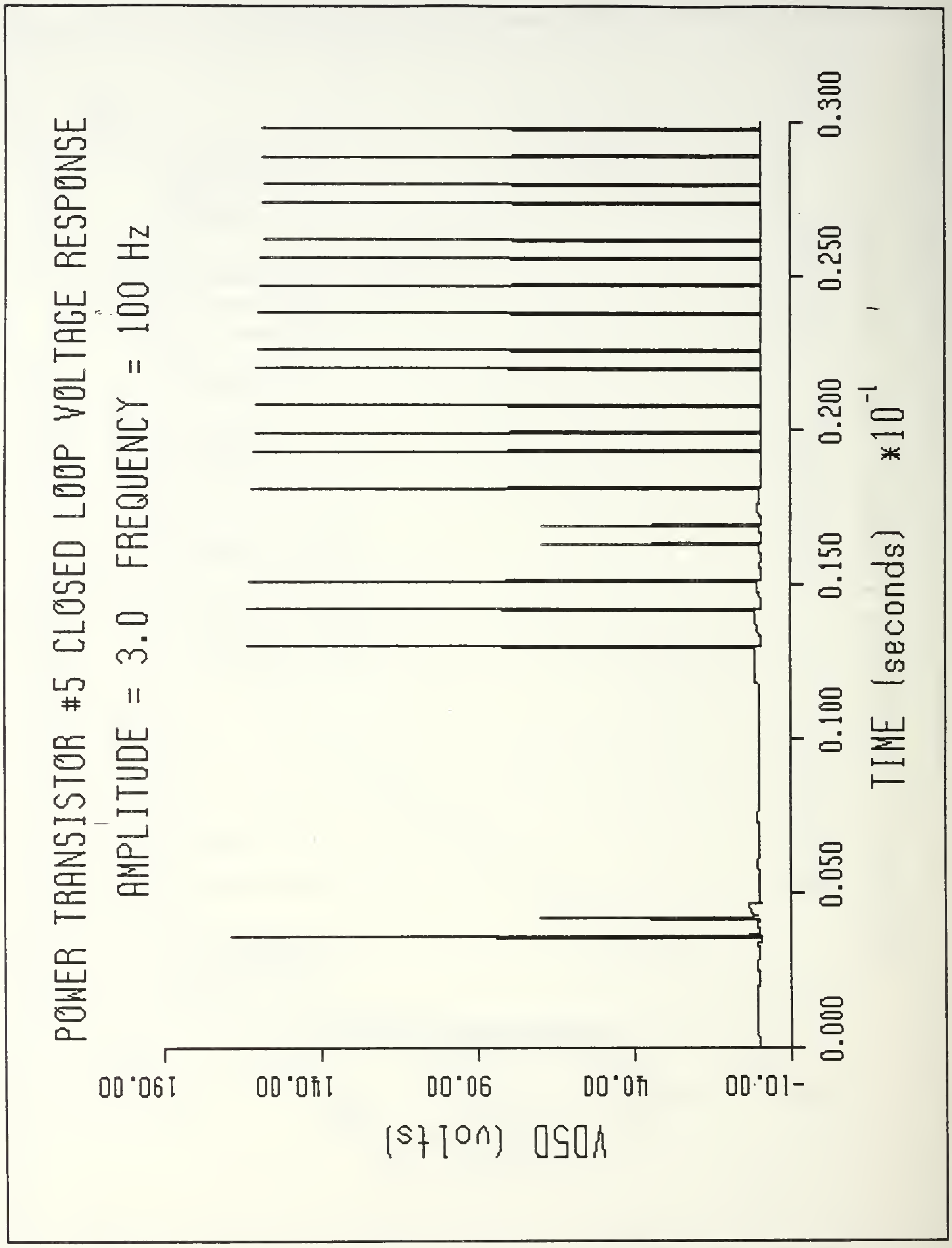


Figure 7.22 Transistor #5 Voltage Sinusoidal Response

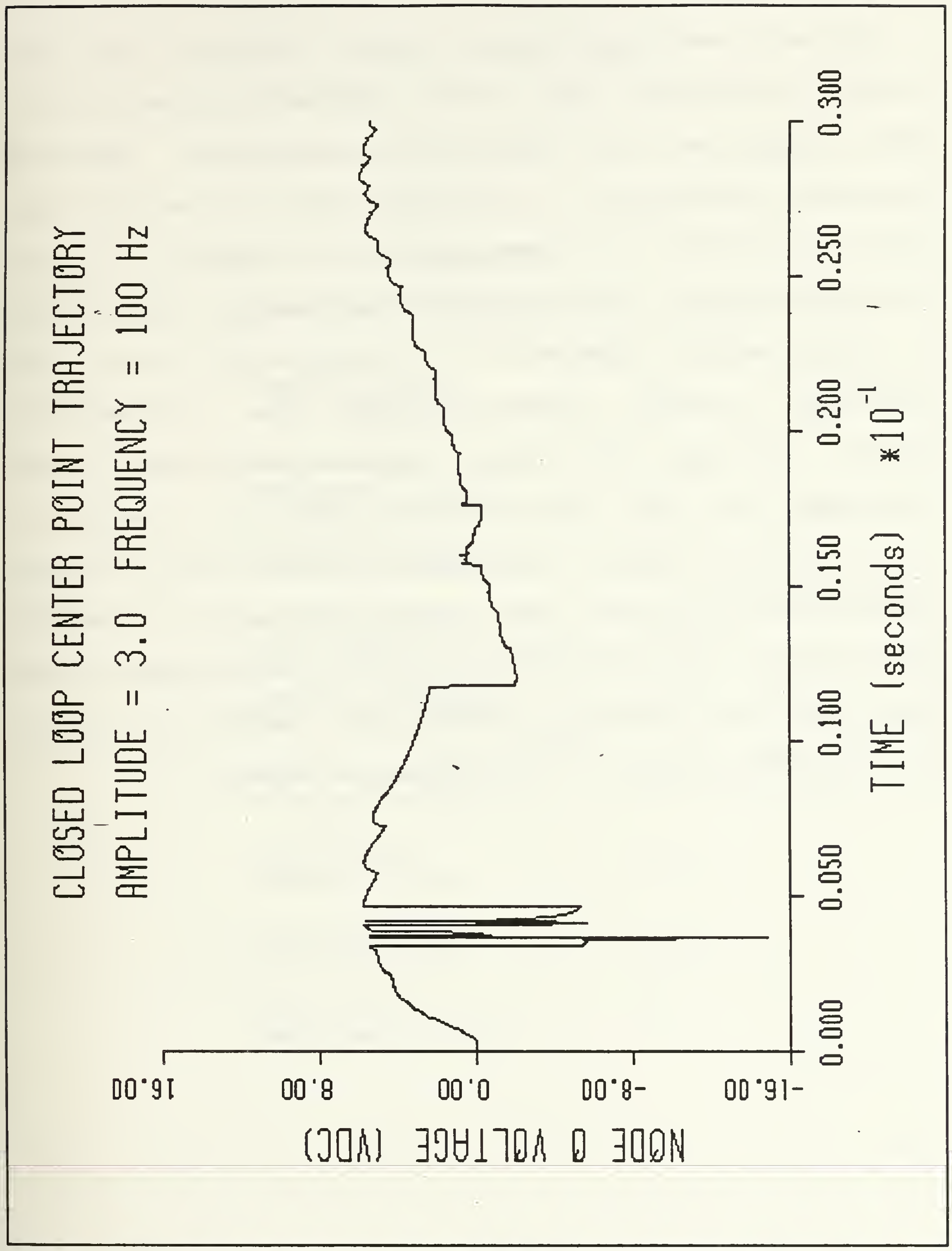


Figure 7.23 Node O Voltage Sinusoidal Response

C. FINAL DESIGN

It has been demonstrated through simulation that the position controller final design parameters specified in Table VI provide robust operational performance. Demanding mechanical performance is achieved with an electronically sensitive brushless dc motor through the adaption of pulse width modulation. The transient waveshaping incorporated in this design appeared to significantly modify the electrical response characteristics when independently studied. However, the coupled electrical-mechanical design performed in this chapter diminishes the impact of waveshaping and relies most heavily on the soft response characteristics of the PWM. Oscillation due to low duty cycle pulse width modulation is apparent during near-steady state conditions, but its effects are filtered by the low pass characteristics of the brushless dc motor.

TABLE VI

SUMMARY OF FINAL DESIGN PARAMETERS

PWM Amplifier Gain (K_{PWM})	3.0
PWM Pulsing Frequency (f_{PWM})	10KHz
PWM Controller Dead Zone (DBAND)	0.0°
Velocity Feedback Gain Coefficient (K_v)	0.001
Position Feedback Gain Coefficient (K_p)	1.0
Bias Threshold Voltage Divider %	50%
Commutation Offset (THADV)	0.0°
Plugging Delay (TDPLUG)	10 μsec
Decay Rate Resistance (RDADJ)	3 Ω

VIII. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

It has been demonstrated through computer simulation that the brushless dc motor has viable application in position control. The electronically demanding environment associated with forced braking and bi-directional motor operation requires that considerable attention be given to the power conditioner's electrical transient response characteristics. The central theme presented in this study involves the design compromises required to exploit the intrinsic high performance of a brushless dc motor without sacrificing operational reliability of its solid state components. This study advances an on-going comprehensive development effort of cruise missile fin control using electromechanical actuation.

Reduced peak voltage conditions associated with commutation switching were attained through transient current waveshaping techniques involving modification of power conditioner circuitry. Pulse width modulation in closed loop position control was observed to provide electrically advantageous response buffering during rotational reversals of the motor.

System performance was initially evaluated in the phase plane and preliminary design parameters based on a reduced order lumped parameter model were identified. Composite analysis of the electromechanical actuator was conducted through computer simulation using the detailed model of the brushless dc motor listed in Appendix A. Following minor power conditioning parameter adjustments, simulated results were highly consistent with system performance observed using linear approximation methods and electrical transient behavior was observed to be very satisfactory. The controller was found to be functionally robust based on response evaluation using small and large step, ramp, and sinusoidal inputs.

The four pole brushless dc motor modeled in this study is based on typical motor specifications and limited physical benchmark measurements of this motor conducted at NWC, China Lake. Consequently, validation of the model is limited to the extent of available performance data. Ongoing cruise missile fin actuator design efforts using brushless dc motors at NWC, China Lake promise a more complete and reliable performance data base for future modeling improvements. The interactive nature of the simulation program permits easy access to motor and controller parameters and facilitates future parameter modification to accommodate updated performance measurements. Validation of the computer simulation was performed not only with comparison of predicted and physically observed behavior, but also with analytical methods. Lumped parameter modeling and state space solutions determined in Chapter VI were used to accurately predict the detailed simulation results of Chapter VII.

B. RECOMMENDATIONS FOR FURTHER STUDY

All analyses performed in this study were based on linear fin actuator load conditions. Mechanical linkage design consideration with inclusion of loading and power transmission effects, such as modeled in Wright's thesis [Ref.12], should be investigated for torsional and stall torque operating conditions.

The numerical accuracy of all computer simulations conducted in this work is limited by the nature of small step trapezoidal integration and should be considered as an area for future improvement. Since convergence criteria is constantly monitored, modification to the integration method may be readily evaluated through observation of numerical convergence behavior.

A study of power dissipation and heat sinking requirements of solid state components is warranted based on the high current demands observed during simulation of position control.

Feasibility of electrical power regeneration during dynamic braking action of the motor was suggested and deserves more extensive evaluation in future studies. Because of the anticipated lengthy duration of missile flight control, adaption of such an energy conservation measure would reduce the demand on the missile power supply and conceivably support size and weight reduction.

Improved modeling of diode response characteristics will enhance the simulation of freewheeling action encountered during commutation switching. Presently, diodes are modeled as either conducting or not conducting, depending on bias conditions. The corresponding diode resistance characteristics, therefore, are discontinuously modeled and require artificial programming techniques to simulate their physical behavior.

APPENDIX A

BRUSHLESS DC MOTOR SIMULATION PROGRAM

```
$NOfloatcalls
$NOdebug
C ... MAIN PROGRAM ...
C      _______________________________________________
C     |                                               |
C     |  ROSSITTO, VS   THESIS    PROF GERBA  03/26/87 |
C     |______________BRUSHLESS_DC_MOTOR_______________|
C
C                         SYSTEM REQUIREMENTS
C
C    This simulation is written for compilation using MS FORTRAN77 V3.31.
C    Three programs: BLDCM1.FOR, BLDCM2.FOR, & BLDCM3.FOR must be
C    compiled and linked. This version uses PLOTWORKS PLOT88 for graphic
C    output support; the library must be included during linking.
C
C    - Hardware Reqmts --> INTEL 8088/8086 family (PC/XT)
C                      or  INTEL 80286 family (AT)
C             {{ INTEL 8087/80287 math coprocessor highly recommended}}
C    - Memory Reqmts --> 640K (RAM resident utility programs may have
C                        to be stripped.)
C    - Storage --> Hard Disk preferred, Minimum 2 Floppy Drive System
C                  For use with floppy drives, virtual memory scheme
C                  requires 360KB data disk. The selection of VM default
C                  drive is menu selectable.
C    - DOS Configuration --> CONFIG.SYS file must contain:
C                                   device=ANSI.SYS
C                                   files=15
C    - Support Files --> BLDCM.INP (formatted input data which is
C                        accessible during execution of program)
C                        BLDCM1.VIR |
C                        BLDCM2.VIR | These 4 files are generated by
C                        BLDCM3.VIR | the simulation program and are
C                        BLDCM4.VIR | used as virtual memory.
C
C                        PROGRAM DESCRIPTION
C          This program simulates the detailed operation of a bipolar,
C     three phase brushless dc motor. Console interaction by the user
C     provides the ability to simulate under a broad range of operating
C     parameters as well as initial conditions. Since the simulation
C     is intended to be used primarily for design purposes, repetitive
C     iterations with saved data are possible.
C          The method of simulation used in this program emulates
C     processing through the use of two nested systems of non-linear
```

```
C     differential equations.  The inner loop serves to describe the
C     electrical system response, while the outer loop describes the
C     electro-mecanical system response.  Both systems of non-linear
C     differential equations are solved using Newton-like iterative
C     convergence schemes. The inner loop is numerically stiff in that
C     the non-linear nature of the diode equivalent resistance allows
C     numerical convergence to two solutions when the diode cutoff
C     threshold is approached. This is dealt with by using a fixed,
C     but relatively small step size and a cautious modified Newton's
C     method of solution.
C          Trapezoidal integration is used for computational speed.
C     Comparison to results attained using Runge-Kutta methods on IBM-
C     370 based CSMP indicate good accuracy.  The first order
C     differential equation solver, TCONST, is an algebraic solver and
C     provides a rapid means of solving an otherwise iterative problem.
C
C     Variable Descriptors are explained throughout the program and,
C     therefore, will not be described here.
C
      IMPLICIT REAL*4 (A-Z)
      COMMON BEGTIM,FINTIM,NPTS,IOPORT,MODEL,XLEN,YLEN,PLEN,PLEN1,
     +       XTITLE,YTITLE,PTITLE,PTIT1
      REAL*4 XTIME(1010)
      INTEGER*2 NTIME,NTERMS,IOPORT,MODEL,NUMIT,NUMIN,XLEN,YLEN,N,
     +        NTIM1,NTIM11,NTIM12,NTIM13,NTIM14,
     +        NTIM21,NTIM22,NTIM23,NTIM32,NTIM33,NTIM34,NTIM35,
     +        ELEMNT,SIM2PL,POSIT,DIR,
     +        NTIM01,NTIM02,NTIM03,NTIM04,NTIM05,NTIM06,HALF,
     +        NTIM47,NTIM48,PMODEL,NCTR,NPTS,AHALF,BHALF,CHALF,
     +        TRIG1,TRIG2,TRIG3,TRIG4,TRIG5,TRIG6,DIRM1,PLUG
      logical*2 TOGGLE
      character*3 DISOPT,DRIVE,DRIVE1
      character*6 ANS1,ANS11,ANS21,ANS27,PRTSEL,NONLIN,TYPE,TYPE1
      character*25 XTITLE,YTITLE,NLCHAR
      character*51 PRTCHR,PTITLE,PTIT1
C
C  ... Introductory Page (1 time good deal!)
      call CLRSCR
      write(*,4)
      PAUSE
C
C  *** Open/Read/Close input data file ***
   13 open(2,FILE='BLDCM.INP',STATUS='OLD',ACCESS='SEQUENTIAL')
         read(2,1000) PMODEL,PRTCHR,RIN,ROUT,RDADJ
         read(2,1020) BEGTIM,FINTIM,PTSPLT,MAXITS,SIM2PL
         read(2,1022) KPWM,KV,E0,EDOT0,TTIME,XORG,YORG
         read(2,1024) RS,RSAT,JL,BL,KTM
         read(2,1026) JM,RA,LA,KBM,THADV,TDPLUG
         read(2,1028) BM,KP,PERIOD,DBAND,KA
         read(2,1030) TYPE,RCUT,STPMAG,RSLOPE
         read(2,1032) SINAMP,SINFRQ,SINPHA,DRIVE
      close(2,STATUS='KEEP')
C
C
C     **************************************
C     *** DISPLAY MAIN MENU SELECTIONS ***
C     **************************************
C
    1 call CLRSCR
      call GOTOXY(8,1)
      write(*,5)
      read(*,'(A)') ANS1
C  ... Hardware Options ...
      if ((ANS1 .eq. 'h') .or. (ANS1 .eq. 'H')) then
C
  101    call CLRSCR
         call GOTOXY(17,24)
         write(*,*)'*** CURRENT PRINTER SELECTION ***'
         call GOTOXY(20,20)
         write(*,*) PRTCHR
         call GOTOXY(10,1)
         write(*,105)
         read(*,'(A)') ANS11
C
C  ... Printer Options ...
         if ((ANS11 .eq. 'p') .or. (ANS11 .eq. 'P')) then
            call PRNOPT(PMODEL,PRTSEL,PRTCHR)
            go to 101
C
C  ... Quit the Hardware Menu ...
         elseif((ANS11 .eq. 'q') .or. (ANS11 .eq. 'Q')) then
            go to 1
         else
            go to 101
         endif
C
C  ... Motor Parameters ...
      elseif ((ANS1 .eq. 'm') .or. (ANS1 .eq. 'M')) then
C
         call MOTPAR(KTM,KBM,RIN,ROUT,RDADJ,RA,LA,BM,BL,JM,JL,
     +                RSAT,RCUT,TTIME,RS,THADV,TDPLUG)
         go to 1
C
C  ... NON-LINEAR ELEMENT SELECTION MENU ...
C
      elseif ((ANS1 .eq. 'n') .or. (ANS1 .eq. 'N')) then
   14    call CLRSCR
         call GOTOXY(21,1)
         write(*,272) NLCHAR
         call GOTOXY(1,1)
         write(*,270) KV,KP
         read(*,'(A)') ANS27
```

```
C  ... RELAY AS NON-LINEAR ELEMENT ...
         if ((ANS27 .eq. 'r') .or. (ANS27 .eq. 'R')) then
            ELEMNT=1
            NLCHAR='RELAY'
 291        call CLRSCR
            NONLIN='R'
            write(*,290) DBAND
            read(*,'(A)') ANS21
C
           if (ANS21 .eq. 'DBAND') then
              call GOTOXY(24,1)
              write(*,'(A\)')'Enter a REAL value for DBAND--> '
              read(*,*) DBAND
              go to 291
           elseif ((ANS21 .eq. 'q') .or. (ANS21 .eq. 'Q')) then
              go to 14
           else
              go to 291
           endif
C  ... PULSE WIDTH MODULATOR AS NON-LINEAR ELEMENT ...
         elseif ((ANS27 .eq. 'p') .or. (ANS27 .eq. 'P')) then
            ELEMNT=3
            NLCHAR='PULSE WIDTH MODULATOR'
 301        call CLRSCR
            NONLIN='P'
            write(*,300) DBAND,PERIOD,KPWM
            read(*,'(A)') ANS21
C
           if (ANS21 .eq. 'DBAND') then
              call GOTOXY(24,1)
              write(*,'(A\)')'Enter a REAL value for DBAND--> '
              read(*,*) DBAND
              go to 301
           elseif (ANS21 .eq. 'PERIOD') then
              call GOTOXY(24,1)
              write(*,'(A\)')'Enter a REAL value for PERIOD--> '
              read(*,*) PERIOD
              go to 301
           elseif (ANS21 .eq. 'KPWM') then
              call GOTOXY(24,1)
              write(*,'(A\)')'Enter a REAL value for KPWM--> '
              read(*,*) KPWM
              go to 301
           elseif ((ANS21 .eq. 'q') .or. (ANS21 .eq. 'Q')) then
              go to 14
           else
              go to 301
           endif
C
         elseif ((ANS27 .eq. 'KV') .or. (ANS27 .eq. 'kv')) then
            call GOTOXY(24,1)
```

```
             write(*,'(A\)')'Enter a REAL value for KV--> '
             read(*,*) KV
             go to 14
C
          elseif ((ANS27 .eq. 'KP') .or. (ANS27 .eq. 'kp')) then
             call GOTOXY(24,1)
             write(*,'(A\)')'Enter a REAL value for KP--> '
             read(*,*) KP
             go to 14
C
          elseif ((ANS27 .eq. 'q') .or. (ANS27 .eq. 'Q')) then
              go to 1
          else
              go to 14
          endif
C
C  ... Simulation Options ...
       elseif ((ANS1 .eq. 'o') .or. (ANS1 .eq. 'O')) then
C
 202      call CLRSCR
C
          DELTIM=(FINTIM-BEGTIM)/(PTSPLT*SIM2PL)
          if (FINTIM/DELTIM .gt. MAXITS) DELTIM =FINTIM/MAXITS
          NTERMS=IFIX(FINTIM/DELTIM)+1
C
          write(*,240) BEGTIM,FINTIM,PTSPLT,MAXITS,SIM2PL,E0,EDOT0,
     +                 XORG,YORG,DRIVE,DELTIM,NTERMS
          read(*,'(A)') ANS21
C
          if (ANS21 .eq. 'BEGTIM') then
             call GOTOXY(24,1)
             write(*,'(A\)')'Enter a REAL value for BEGTIM--> '
             read(*,*) BEGTIM
             go to 202
          elseif (ANS21 .eq. 'FINTIM') then
             call GOTOXY(24,1)
             write(*,'(A\)')'Enter a REAL value for FINTIM--> '
             read(*,*) FTIME
             if (FTIME .le. BEGTIM) then
               call CLRSCR
               call GOTOXY(10,10)
               write(*,*) 'INVALID FINTIM ... FINTIM must be > BEGTIM'
               go to 202
             endif
             FINTIM=FTIME
             go to 202
          elseif (ANS21 .eq. 'PTSPLT') then
             call GOTOXY(24,1)
             write(*,'(A\)')'Enter a REAL value for PTSPLT--> '
             read(*,*) PTSPLT
             go to 202
```

```
         elseif (ANS21 .eq. 'MAXITS') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for MAXITS--> '
            read(*,*) MAXITS
            go to 202
         elseif (ANS21 .eq. 'SIM2PL') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a INTEGER value for SIM2PL--> '
            read(*,*) SIM2PL
            go to 202
         elseif (ANS21 .eq. 'E0') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for E0 (degrees)--> '
            read(*,*) E0
            go to 202
         elseif (ANS21 .eq. 'EDOT0') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for EDOT0 (deg/sec)--> '
            read(*,*) EDOT0
            go to 202
         elseif (ANS21 .eq. 'XORG') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for XORG--> '
            read(*,*) XORG
            go to 202
         elseif (ANS21 .eq. 'YORG') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for YORG--> '
            read(*,*) YORG
            go to 202
         elseif (ANS21 .eq. 'DRIVE') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter Drive (A,B,C) for data storage --> '
            read(*,'(A)') DRIVE1
            if ((DRIVE1 .eq. 'A') .or. (DRIVE1 .eq. 'a')) then
               DRIVE='A'
            elseif ((DRIVE1 .eq. 'B') .or. (DRIVE1 .eq. 'b')) then
               DRIVE='B'
            elseif ((DRIVE1 .eq. 'C') .or. (DRIVE1 .eq. 'c')) then
               DRIVE='C'
            else
               call CLRSCR
               call GOTOXY(10,20)
               write(*,*) 'Invalid Drive Specified - Enter A, B,or C'
               PAUSE
            endif
            go to 202
C  ... Quit Simulation Options Menu ...
         elseif (ANS21 .eq. 'Q') then
            go to 1
         else
```

```
               go to 202
            end if
C
C  ... Command Input Selection ...
         elseif ((ANS1 .eq. 'c') .or. (ANS1 .eq. 'C')) then
C
 203        call CLRSCR
C
            write(*,245) TYPE,STPMAG,RSLOPE,SINAMP,SINFRQ,SINPHA
            read(*,'(A)') ANS21
C
            if (ANS21 .eq. 'TYPE') then
               call GOTOXY(24,1)
               write(*,'(A\)')'Enter a STEP, RAMP, or SINE--> '
               read(*,'(A)') TYPE1
               if ((TYPE1 .ne. 'STEP') .and. (TYPE1 .ne. 'RAMP') .and.
     +              (TYPE1 .ne. 'SINE')) then
                  call CLRSCR
                  call GOTOXY(10,10)
                  write(*,*) 'Invalid Selection !!!'
                  call GOTOXY(20,1)
                  PAUSE
                  go to 203
               else
                  TYPE=TYPE1
               endif
C
               go to 203
            elseif (ANS21 .eq. 'STPMAG') then
               call GOTOXY(24,1)
               write(*,'(A\)')'Enter a REAL value for STPMAG--> '
               read(*,*) STPMAG
               go to 203
            elseif (ANS21 .eq. 'RSLOPE') then
               call GOTOXY(24,1)
               write(*,'(A\)')'Enter a REAL value for RSLOPE--> '
               read(*,*) RSLOPE
               go to 203
            elseif (ANS21 .eq. 'SINAMP') then
               call GOTOXY(24,1)
               write(*,'(A\)')'Enter a REAL value for SINAMP--> '
               read(*,*) SINAMP
               go to 203
            elseif (ANS21 .eq. 'SINFRQ') then
               call GOTOXY(24,1)
               write(*,'(A\)')'Enter a REAL value for SINFRQ--> '
               read(*,*) SINFRQ
               go to 203
            elseif (ANS21 .eq. 'SINPHA') then
               call GOTOXY(24,1)
               write(*,'(A\)')'Enter a REAL value for SINPHA--> '
```

```
              read(*,*) SINPHA
              go to 203
C  ... Quit Simulation Options Menu ...
           elseif (ANS21 .eq. 'Q') then
              go to 1
           else
              go to 203
           end if
C  ... Save Options to File ...
        elseif ((ANS1 .eq. 's') .or. (ANS1 .eq. 'S')) then
C
C       *******************************************
C       *** OPEN/WRITE/CLOSE INPUT DATA FILE ***
C       *******************************************
C
        open(2,FILE='BLDCM.INP',STATUS='OLD',ACCESS='SEQUENTIAL')
           write(2,1000) PMODEL,PRTCHR,RIN,ROUT,RDADJ
           write(2,1020) BEGTIM,FINTIM,PTSPLT,MAXITS,SIM2PL
           write(2,1022) KPWM,KV,E0,EDOT0,TTIME,XORG,YORG
           write(2,1024) RS,RSAT,JL,BL,KTM
           write(2,1026) JM,RA,LA,KBM,THADV,TDPLUG
           write(2,1028) BM,KP,PERIOD,DBAND,KA
           write(2,1030) TYPE,RCUT,STPMAG,RSLOPE
           write(2,1032) SINAMP,SINFRQ,SINPHA,DRIVE
        close(2,STATUS='KEEP')
C
            go to 1
C
C  ... Run the Program ...
        elseif ((ANS1 .eq. 'r') .or. (ANS1 .eq. 'R')) then
           go to 2
C
C  ... Quit the Program ...
        elseif ((ANS1 .eq. 'q') .or. (ANS1 .eq. 'Q')) then
            stop
        else
            go to 1
        endif
C
C  ...  Open an output data file  ...
    2  continue
        if (DRIVE .eq. 'A') then
           OPEN(4,FILE='a:BLDCM1.VIR',STATUS='NEW')
           OPEN(5,FILE='a:BLDCM2.VIR',STATUS='NEW')
           OPEN(6,FILE='a:BLDCM3.VIR',STATUS='NEW')
           OPEN(7,FILE='a:BLDCM4.VIR',STATUS='NEW')
        elseif (DRIVE .eq. 'B') then
           OPEN(4,FILE='b:BLDCM1.VIR',STATUS='NEW')
           OPEN(5,FILE='b:BLDCM2.VIR',STATUS='NEW')
           OPEN(6,FILE='b:BLDCM3.VIR',STATUS='NEW')
           OPEN(7,FILE='b:BLDCM4.VIR',STATUS='NEW')
```

```
      elseif (DRIVE .eq. 'C') then
         OPEN(4,FILE='c:BLDCM1.VIR',STATUS='NEW')
         OPEN(5,FILE='c:BLDCM2.VIR',STATUS='NEW')
         OPEN(6,FILE='c:BLDCM3.VIR',STATUS='NEW')
         OPEN(7,FILE='c:BLDCM4.VIR',STATUS='NEW')
      endif
C
C  *** Listing of constants ***
C
      PI = 3.14159265
      KADJ=0.63
      KK3 = 3.590
      TN2=.1
      N=30.0
      TCIMC=0.01
      TLL=0.0
      VSAT=.4
      REVTIM=0.1
      VN1=0.
      VN2=0.
      VSGREF=30.
      KINT=10000.
      KRAMP=18000.
      VSG=0.
      VINHF1=75.0
      REDRAT=.1
C
C  Initial Conditions
      TRIG1=0
      TRIG2=0
      TRIG3=0
      TRIG4=0
      TRIG5=0
      TRIG6=0
      WM=0.
      THETA=0.
      PTHETA=0.0
      THETA1=0.
      IMA=0.0
      IMB=0.0
      IMC=0.0
      IMAB=0.0
      IMBC=0.0
      IMCA=0.0
      NCTR=0
      NPTS=0
      NTIM1=0
      NTIM01=0
      NTIM02=0
      NTIM03=0
      NTIM04=0
```

```
NTIM05=0
NTIM06=0
NTIM11=0
NTIM12=0
NTIM13=0
NTIM14=0
NTIM21=0
NTIM22=0
NTIM01=0
NTIM02=0
NTIM03=0
NTIM04=0
NTIM05=0
NTIM06=0
NTIM32=0
NTIM33=0
NTIM34=0
NTIM35=0
ICQ1=.75
ICQ2=.75
ICQ3=.75
ICQ4=.75
ICQ5=.75
ICQ6=.75
ICIMAB=0.
ICIMBC=0.
ICIMCA=0.
ICTMF=0.
ICWM=0.
X1=0.0
F1=0.0
F2=0.0
X3=0.0
ZA3=0.0
ZB3=0.0
ZC3=0.0
TSTART=0.0
TOGGLE=.true.
VIN=0.
PREV5=0.
CURV5=0.
HOLD1=0.
PREV2=0.
PREV2=0.
PREV3=0.
YY2=0.
YY3=0.
YY4=0.
YDM12=0.
YDM13=0.
YDM14=0.
```

```
      YD2=0.
      YD3=0.
      YD4=0.
      YDDM12=0.
      YDDM13=0.
      YDDM14=0.
      YDD2=0.
      YDD3=0.
      YDD4=0.
      PREV7=0.
      CURV7=0.
      HOLD3=0.
      PLUG=0
      TFPLUG=0.
      DIRM1=0
C
C  RELATIONSHIPS
      KT=KTM*KADJ
      KB=KBM*KADJ
      BLP=BL/(N**2)
      JLP=JL/(N**2)
      J=JM+JLP
      B=BM+BLP
      A1=LA/RA
      A2=J/B
      A3=LA/(RA+RSAT)
      RS1=RS/2.
      RS2=RS/2.
      VINIC=15.0/KINT
      VINHAF=VINHF1
C  ... Initial conditions for THETA(fin,degrees) and Omega(fin,degrees).
      E0RAD=E0*PI/(180.*REDRAT)
      EDOT0R=EDOT0*PI/(180.*REDRAT)
      if (KP .ne. 0.) then
         WM0=-EDOT0R/KP
         THETA0=-E0RAD/KP
      elseif (KP .eq. 0.) then
         WM0=-EDOT0R
         THETA0=-E0RAD
      endif
      WM=WM0
      X3=THETA0
C
C  ... Output Simulation Options to Output Data File ...
C
C  ****************************************
C  ***** Time Generator ... 0-50ms *****
C  ****************************************
      DELTIM=(FINTIM-BEGTIM)/(PTSPLT*SIM2PL)
      if (FINTIM/DELTIM .gt. MAXITS) DELTIM =FINTIM/MAXITS
      NTERMS=IFIX(FINTIM/DELTIM)+1
      SPACE=DELTIM/2.
C
C *** Clear Screen & Home Cursor ***
      call CLRSCR
      call GOTOXY(10,29)
      write(*,*) 'Elapsed Simulation Time'
      call GOTOXY(12,41)
      write(*,*) 'seconds'
      call GOTOXY(15,1)
      write(*,15) BEGTIM,FINTIM,DELTIM,NTERMS
   15 format(22X,'Simulation Start Time --> ',F8.7,/,
     +        23X,'Simulation Stop Time ---> ',F8.7,/,
     +        23X,'Simulation Step Size ---> ',F8.7,/,
     +        23X,'Total Number of Steps --> ',I4)
      call GOTOXY(21,1)
C
      if ((NONLIN .eq. 'r') .or. (NONLIN .eq. 'R')) then
       write(*,*) '                      *** NON-LINEAR ELEMENT IS RELAY
     + ***'
      elseif ((NONLIN .eq. 'p') .or. (NONLIN .eq. 'P')) then
       write(*,*) '                       *** NON-LINEAR ELEMENT IS PWM
     + ***'
      else
       write(*,*) '             *** NON-LINEAR ELEMENT NOT SELECTED ***'
       write(*,*) '                   ... Return to Main Menu ...'
       PAUSE
       go to 1
      endif
C
      DO 100 NTIME = 1,NTERMS
        TIME = (NTIME-1)*DELTIM
C  *** Output Elapsed Simulation Time to Display ***
C
      call GOTOXY(12,33)
      write(*,93) TIME
   93 format(F7.6)
C
C  ... Command Input Signal Generator ...
         if (TYPE .eq. 'STEP') then
            ORDER=STPMAG
         elseif (TYPE .eq. 'RAMP') then
            ORDER=RSLOPE*TIME
         elseif (TYPE .eq. 'SINE') then
            ORDER=SINAMP*sin(SINFRQ*TIME+SINPHA)
         endif
C
        VSGDEL=(VSGREF-VSG)/2.
        P1=-.5
        P2=.5
        call DEADSP(P1,P2,VSGDEL,VSGERR)
        call INTGRL(NTIME,NTIM21,DELTIM,VINIC,PREV5,VSGERR,
     +             CURV5,HOLD1,VININT)
        VINHFG=KINT*VININT
C
C   *******************************************
C   ***** INITIAL ITERATIVE CONDITIONS *****
C   *******************************************
      if (NTIME .eq. 2) then
         WM=WM+(ORDER-X3)*1.E-3
         X3=X3+(ORDER-X3)*1.E-3
         ZA3=1.E-6
         ZB3=-1.E-4
         ZC3=1.E-4
      endif
      HALF=0
C   ************************************************************
C   ******************** ITERATIVE LOOP **********************
C   ************************************************************
      do 500 NUMIT=1,20
        THETA=X3
C
C  *** Phase angles ***
        BEMFA=(3.0*SIN(2.0*THETA+(11.0*PI/6.0))+.590*SIN(10.0*
     +       THETA+(1.0*PI/6.0)))
        BEMFB=(3.0*SIN(2.0*THETA+(7.0*PI/6.0))+.590*SIN(10.0*
     +        THETA+(5.0*PI/6.0)))
        BEMFC=(3.0*SIN(2.0*THETA+(3.0*PI/6.0))+.590*SIN(10.0*
     +        THETA+(9.0*PI/6.0)))
C  ***  Normalize leg EMF ***
        VEMFA = BEMFA * KB/KK3 * WM
        VEMFB = BEMFB * KB/KK3 * WM
        VEMFC = BEMFC * KB/KK3 * WM
        VEMFAC = VEMFA - VEMFC
        VEMFBA = VEMFB - VEMFA
        VEMFCB = VEMFC - VEMFB
C
        call COMADV(THETA,PI,float(DIR)*THADV,THCON,THRST)
        call HALL(THCON,SE1,SE2,SE3)
C
        THETAF=REDRAT*THETA*180./PI
        OMEGAF=REDRAT*WM*180./PI
        POSERR=ORDER-KP*THETAF-KV*OMEGAF
C
C  ... Utilization of Non-Linear Element ...
C  ... PULSE WIDTH MODULATOR ...
      if ((NONLIN .eq. 'p') .or. (NONLIN .eq. 'P')) then
         call PWMOD(TIME,NUMIT,TSTART,PERIOD,TOGGLE,POSERR,
     +             DBAND,VIF,VIB,DIR,VREF,THRESH,KPWM)
C  ... IDEAL RELAY ...
      elseif ((NONLIN .eq. 'r') .or. (NONLIN .eq. 'R')) then
         call RELAY(POSERR,DBAND,VIF,VIB,DIR)
      else
```

```
            call GOTOXY(21,1)
            write(*,*) '          *** NON-LINEAR ELEMENT NOT SELECTED ***'
            write(*,*) '                  ... Return to Main Menu ...'
            PAUSE
            go to 1
         endif
         VIN=VIF-VIB
         IL=VIN/(2.0*RCUT)
C
C    *************************************************************
C    ***** INITIAL ITERATIVE CONDITIONS FOR INNER ITERATION *****
C    *************************************************************
C
            TRIG1 = 0
            TRIG2 = 0
            TRIG3 = 0
            TRIG4 = 0
            TRIG5 = 0
            TRIG6 = 0
C
         if ((TIME .ge. TFPLUG) .or. (TIME .eq. TOPLUG)) then
            if (float(DIRM1)*float(DIR) .lt. 0.) then
               TOPLUG=TIME
               TFPLUG=TOPLUG+TDPLUG
               PLUG=1
            else
               TOPLUG=0.
               TFPLUG=0.
               PLUG=0
            endif
         endif
C
           call TRANSW(TIME,REVTIM,BEMFA,BEMFB,BEMFC,BEMFT,VEMFA,
     +                VEMFB,VEMFC,VIB,VIF,IM,IMA,IMB,IMC,VN1,VN2,SW1,
     +                SW2,SW3,SW4,SW5,SW6,THCON,THCON1,RSAT,POSIT,DIR,
     +                VD1D,VD2D,VD3D,VD4D,VD5D,VD6D,RIN,ROUT,RS,
     +                REQA1,REQA2,REQB1,REQB2,REQC1,REQC2,IAB,IBC,ICA,
     +                PVAO,PVBO,PVCO,NODE,TRIG1,TRIG2,TRIG3,TRIG4,
     +                TRIG5,TRIG6,RA,PLUG,VAIND,VBIND,VCIND)
C
           call TCONST(ICQ1,.75-SW1,TTIME,NTIME,NTIM01,DELTIM,Q1EXP)
           call TCONST(ICQ2,.75-SW2,TTIME,NTIME,NTIM02,DELTIM,Q2EXP)
           call TCONST(ICQ3,.75-SW3,TTIME,NTIME,NTIM03,DELTIM,Q3EXP)
           call TCONST(ICQ4,.75-SW4,TTIME,NTIME,NTIM04,DELTIM,Q4EXP)
           call TCONST(ICQ5,.75-SW5,TTIME,NTIME,NTIM05,DELTIM,Q5EXP)
           call TCONST(ICQ6,.75-SW6,TTIME,NTIME,NTIM06,DELTIM,Q6EXP)
C
           call LIMIT(RSAT,RCUT,2.0*RCUT*Q1EXP,RQ1)
           call LIMIT(RSAT,RCUT,2.0*RCUT*Q2EXP,RQ2)
           call LIMIT(RSAT,RCUT,2.0*RCUT*Q3EXP,RQ3)
           call LIMIT(RSAT,RCUT,2.0*RCUT*Q4EXP,RQ4)
```

```
        call LIMIT(RSAT,RCUT,2.0*RCUT*Q5EXP,RQ5)
        call LIMIT(RSAT,RCUT,2.0*RCUT*Q6EXP,RQ6)
C
        REQA1=RQ1*RD1/(RQ1+RD1)
        REQA2=RQ2*RD2/(RQ2+RD2)
        REQB1=RQ3*RD3/(RQ3+RD3)
        REQB2=RQ4*RD4/(RQ4+RD4)
        REQC1=RQ5*RD5/(RQ5+RD5)
        REQC2=RQ6*RD6/(RQ6+RD6)
C
        ASIGN=ZA3
        BSIGN=ZB3
        CSIGN=ZC3
C
        AHALF=0
        BHALF=0
        CHALF=0
C
C    ****************************
C    ***** START INNER LOOP *****
C    ****************************
C
      do 650 NUMIN=1,20
         IMA=ZA3
         IMB=ZB3
         IMC=ZC3
C
         CALL DERIV(DELTIM,NTIME,NTIM12,0.0,PREV2,IMA,YY2,YDM12,YD2,
     +            YDDM12,YDD2,DIADT)
         CALL DERIV(DELTIM,NTIME,NTIM13,0.0,PREV3,IMB,YY3,YDM13,YD3,
     +            YDDM13,YDD3,DIBDT)
         CALL DERIV(DELTIM,NTIME,NTIM14,0.0,PREV4,IMC,YY4,YDM14,YD4,
     +            YDDM14,YDD4,DICDT)
         VAIND=LA*DIADT
         VBIND=LA*DIBDT
         VCIND=LA*DICDT
C
         PVAO=IMA*(RA+RIN/2.)+VAIND
         PVBO=IMB*(RA+RIN/2.)+VBIND
         PVCO=IMC*(RA+RIN/2.)+VCIND
C
         VAO=PVAO+VEMFA
         VBO=PVBO+VEMFB
         VCO=PVCO+VEMFC
C
         call TRANSW(TIME,REVTIM,BEMFA,BEMFB,BEMFC,BEMFT,VEMFA,
     +             VEMFB,VEMFC,VIB,VIF,IM,IMA,IMB,IMC,VN1,VN2,SW1,
     +             SW2,SW3,SW4,SW5,SW6,THCON,THCON1,RSAT,POSIT,DIR,
     +             VD1D,VD2D,VD3D,VD4D,VD5D,VD6D,RIN,ROUT,RS,
     +             REQA1,REQA2,REQB1,REQB2,REQC1,REQC2,IAB,IBC,ICA,
     +             PVAO,PVBO,PVCO,NODE,TRIG1,TRIG2,TRIG3,TRIG4,
     +          TRIG5,TRIG6,RA,PLUG,VAIND,VBIND,VCIND)
C
       call LIMIT(-.7,800.0,VD1D,VD1D)
       call LIMIT(-.7,800.0,VD2D,VD2D)
       call LIMIT(-.7,800.0,VD3D,VD3D)
       call LIMIT(-.7,800.0,VD4D,VD4D)
       call LIMIT(-.7,800.0,VD5D,VD5D)
       call LIMIT(-.7,800.0,VD6D,VD6D)
C
       call FCNSW(VD1D+.6,RSAT,RSAT,RCUT,RDX1)
       call FCNSW(VD2D+.6,RSAT,RSAT,RCUT,RDX2)
       call FCNSW(VD3D+.6,RSAT,RSAT,RCUT,RDX3)
       call FCNSW(VD4D+.6,RSAT,RSAT,RCUT,RDX4)
       call FCNSW(VD5D+.6,RSAT,RSAT,RCUT,RDX5)
       call FCNSW(VD6D+.6,RSAT,RSAT,RCUT,RDX6)
C
       RD1=RDX1+RDADJ
       RD2=RDX2+RDADJ
       RD3=RDX3+RDADJ
       RD4=RDX4+RDADJ
       RD5=RDX5+RDADJ
       RD6=RDX6+RDADJ
C
       REQA1=RQ1*RD1/(RQ1+RD1)
       REQA2=RQ2*RD2/(RQ2+RD2)
       REQB1=RQ3*RD3/(RQ3+RD3)
       REQB2=RQ4*RD4/(RQ4+RD4)
       REQC1=RQ5*RD5/(RQ5+RD5)
       REQC2=RQ6*RD6/(RQ6+RD6)
C
       REQAS1=REQA1+RS1+ROUT/2.
       REQAS2=REQA2+RS2+ROUT/2.
       REQBS1=REQB1+RS1+ROUT/2.
       REQBS2=REQB2+RS2+ROUT/2.
       REQCS1=REQC1+RS1+ROUT/2.
       REQCS2=REQC2+RS2+ROUT/2.
C
       VANTH=VN1*REQAS2/(REQAS1+REQAS2)+VN2*REQAS1/(REQAS1+REQAS2)
       VBNTH=VN1*REQBS2/(REQBS1+REQBS2)+VN2*REQBS1/(REQBS1+REQBS2)
       VCNTH=VN1*REQCS2/(REQCS1+REQCS2)+VN2*REQCS1/(REQCS1+REQCS2)
C
       REQA=REQAS1*REQAS2/(REQAS1+REQAS2)
       REQB=REQBS1*REQBS2/(REQBS1+REQBS2)
       REQC=REQCS1*REQCS2/(REQCS1+REQCS2)
C
       REQAB=2.0*RA+1.0*RIN+REQA+REQB
       REQBC=2.0*RA+1.0*RIN+REQB+REQC
       REQCA=2.0*RA+1.0*RIN+REQC+REQA
C
       IAB=(VANTH-VBNTH)/REQAB
       IBC=(VBNTH-VCNTH)/REQBC
```

```
          ICA=(VCNTH-VANTH)/REQCA
C
          ABTAU=2.0*LA/REQAB
          BCTAU=2.0*LA/REQBC
          CATAU=2.0*LA/REQCA
C
C  *** DISCHARGE OF PHASE CURRENTS (FREEWHEELING DIODES) ***
          if (PLUG .eq. 1) then
             IAB=0.
             IBC=0.
             ICA=0.
          elseif ((POSIT .eq. 1) .or. (POSIT .eq. 4)) then
             IAB=0.
             ICA=0.
          elseif ((POSIT .eq. 2) .or. (POSIT .eq. 5)) then
             IBC=0.
             ICA=0.
          elseif ((POSIT .eq. 3) .or. (POSIT .eq. 6)) then
             IAB=0.
             IBC=0.
          endif
C
          call TCONST(ICIMAB,IAB,ABTAU,NTIME,NTIM32,DELTIM,IMAB)
          call TCONST(ICIMBC,IBC,BCTAU,NTIME,NTIM33,DELTIM,IMBC)
          call TCONST(ICIMCA,ICA,CATAU,NTIME,NTIM34,DELTIM,IMCA)
C
          FA3=IMAB-IMCA-ZA3
          FB3=IMBC-IMAB-ZB3
          FC3=IMCA-IMBC-ZC3
C
          IMA=IMAB-IMCA
          IMB=IMBC-IMAB
          IMC=IMCA-IMBC
C
          IM=(abs(IMA)+abs(IMB)+abs(IMC))/2.
C
C    *******************************************
C    ***** MODIFIED LINEAR INTERPOLATION *****
C    *******************************************
        if (NTIME .eq. 1) go to 550
C
        if (NUMIN .eq. 1) then
           ZA1=ZA3
           ZB1=ZB3
           ZC1=ZC3
           FA1=FA3
           FB1=FB3
           FC1=FC3
           ZA3=IMA
           ZB3=IMB
           ZC3=IMC
```

```
            go to 650
         elseif (NUMIN .eq. 2) then
            ZA2=ZA3
            ZB2=ZB3
            ZC2=ZC3
            FA2=FA3
            FB2=FB3
            FC2=FC3
            ASIGN=FA3
            BSIGN=FB3
            CSIGN=FC3
            if (abs(FA1-FA2) .eq. 0.) FA2=.5*FA2+1.E-6
            if (abs(FB1-FB2) .eq. 0.) FB2=.5*FB2+1.E-6
            if (abs(FC1-FC2) .eq. 0.) FC2=.5*FC2+1.E-6
            if (abs(FA1-FA2) .ne. 0.) ZA3=ZA2-FA2*(ZA1-ZA2)/(FA1-FA2)
            if (abs(FB1-FB2) .ne. 0.) ZB3=ZB2-FB2*(ZB1-ZB2)/(FB1-FB2)
            if (abs(FC1-FC2) .ne. 0.) ZC3=ZC2-FC2*(ZC1-ZC2)/(FC1-FC2)
            go to 650
         else
C ... "A" Leg ...
            if (FA3 .ne. 0.) then
             if (FA1*FA2 .lt. 0.) then
               if (FA1*FA3 .lt. 0.) then
                 ZA2=ZA3
                 FA2=FA3
                 if (FA3*ASIGN .gt. 0.) FA1=FA1/2.
                 ZA3=ZA2-FA2*(ZA2-ZA1)/(FA2-FA1)
               elseif (FA1*FA3 .gt. 0.) then
                 ZA1=ZA3
                 FA1=FA3
                 if (FA3*ASIGN .gt. 0.) FA2=FA2/2.
                 ZA3=ZA2-FA2*(ZA2-ZA1)/(FA2-FA1)
               endif
             elseif (FA1*FA2 .gt. 0.) then
C ...Cautious forward iteration using halving and checking scheme in
C    unbracketed region.
               if (AHALF .eq. 0) then
                 ZA1=ZA2
                 ZA2=ZA3
                 FA1=FA2
                 FA2=FA3
                 ZA3=ZA1+(ZA2-ZA1)/2.
                 AHALF=1
               elseif (AHALF .eq. 1) then
                 if (FA1*FA3 .lt. 0.) then
                   AHALF=0
                   ZA2=ZA3
                   FA2=FA3
                   ZA3=ZA2-FA2*(ZA2-ZA1)/(FA2-FA1)
                 elseif (FA1*FA3 .gt. 0.) then
                   AHALF=0
```

```
                  ZA1=ZA2
                  ZA2=ZA3
                  FA1=FA2
                  FA2=FA3
                  if (abs(FA2-FA1) .eq. 0.) FA2=FA2/2.
                  if (abs(FA2-FA1).ne.0.) ZA3=ZA2-FA2*(ZA2-ZA1)/(FA2-FA1)
                endif
              endif
            elseif (FA1*FA2 .eq. 0.) then
                ZA1=ZA2
                ZA2=ZA3
                FA1=FA2
                FA2=FA3
                if (abs(FA2-FA1) .eq. 0.) FA2=FA2/2.
                if (abs(FA2-FA1) .ne. 0.) ZA3=ZA2-FA2*(ZA2-ZA1)/(FA2-FA1)
            endif
           endif
C ... "B" Leg ...
           if (FB3 .ne. 0.) then
            if (FB1*FB2 .lt. 0.) then
              if (FB1*FB3 .lt. 0.) then
                ZB2=ZB3
                FB2=FB3
                if (FB3*BSIGN .gt. 0.) FB1=FB1/2.
                ZB3=ZB2-FB2*(ZB2-ZB1)/(FB2-FB1)
              elseif (FB1*FB3 .gt. 0.) then
                ZB1=ZB3
                FB1=FB3
                if (FB3*BSIGN .gt. 0.) FB2=FB2/2.
                ZB3=ZB2-FB2*(ZB2-ZB1)/(FB2-FB1)
              endif
            elseif (FB1*FB2 .gt. 0.) then
C ...Cautious forward iteration using halving and checking scheme in
C    unbracketed region.
              if (BHALF .eq. 0) then
                ZB1=ZB2
                ZB2=ZB3
                FB1=FB2
                FB2=FB3
                ZB3=ZB1+(ZB2-ZB1)/2.
                BHALF=1
              elseif (BHALF .eq. 1) then
                if (FB1*FB3 .lt. 0.) then
                  BHALF=0
                  ZB2=ZB3
                  FB2=FB3
                  ZB3=ZB2-FB2*(ZB2-ZB1)/(FB2-FB1)
                elseif (FB1*FB3 .gt. 0.) then
                  BHALF=0
                  ZB1=ZB2
                  ZB2=ZB3
                  FB1=FB2
                  FB2=FB3
                  if (abs(FB2-FB1) .eq. 0.) FB2=FB2/2.
                  if (abs(FB2-FB1).ne.0.) ZB3=ZB2-FB2*(ZB2-ZB1)/(FB2-FB1)
                endif
              endif
            elseif (FB1*FB2 .eq. 0.) then
                ZB1=ZB2
                ZB2=ZB3
                FB1=FB2
                FB2=FB3
                if (abs(FB2-FB1) .eq. 0.) FB2=FB2/2.
                if (abs(FB2-FB1) .ne. 0.) ZB3=ZB2-FB2*(ZB2-ZB1)/(FB2-FB1)
            endif
           endif
C ... "C" Leg ...
           if (FC3 .ne. 0.) then
            if (FC1*FC2 .lt. 0.) then
              if (FC1*FC3 .lt. 0.) then
                ZC2=ZC3
                FC2=FC3
                if (FC3*CSIGN .gt. 0.) FC1=FC1/2.
                ZC3=ZC2-FC2*(ZC2-ZC1)/(FC2-FC1)
              elseif (FC1*FC3 .gt. 0.) then
                ZC1=ZC3
                FC1=FC3
                if (FC3*CSIGN .gt. 0.) FC2=FC2/2.
                ZC3=ZC2-FC2*(ZC2-ZC1)/(FC2-FC1)
              endif
            elseif (FC1*FC2 .gt. 0.) then
C ...Cautious forward iteration using halving and checking scheme in
C    unbracketed region.
              if (CHALF .eq. 0) then
                ZC1=ZC2
                ZC2=ZC3
                FC1=FC2
                FC2=FC3
                ZC3=ZC1+(ZC2-ZC1)/2.
                CHALF=1
              elseif (CHALF .eq. 1) then
                if (FC1*FC3 .lt. 0.) then
                  CHALF=0
                  ZC2=ZC3
                  FC2=FC3
                  ZC3=ZC2-FC2*(ZC2-ZC1)/(FC2-FC1)
                elseif (FC1*FC3 .gt. 0.) then
                  CHALF=0
                  ZC1=ZC2
                  ZC2=ZC3
                  FC1=FC2
                  FC2=FC3
                if (abs(FC2-FC1) .eq. 0.) FC2=FC2/2.
                if (abs(FC2-FC1).ne.0.) ZC3=ZC2-FC2*(ZC2-ZC1)/(FC2-FC1)
              endif
            endif
          elseif (FC1*FC2 .eq. 0.) then
              ZC1=ZC2
              ZC2=ZC3
              FC1=FC2
              FC2=FC3
              if (abs(FC2-FC1) .eq. 0.) FC2=FC2/2.
              if (abs(FC2-FC1) .ne. 0.) ZC3=ZC2-FC2*(ZC2-ZC1)/(FC2-FC1)
          endif
         endif
      endif
C
      ASIGN=FA3
      BSIGN=FB3
      CSIGN=FC3
C
      if (abs(ZA3) .gt. 1.E-4) RERRZA=abs(FA3/ZA3)
      if (abs(ZA3) .le. 1.E-4) RERRZA=abs(FA3)
      if (abs(ZB3) .gt. 1.E-4) RERRZB=abs(FB3/ZB3)
      if (abs(ZB3) .le. 1.E-4) RERRZB=abs(FB3)
      if (abs(ZC3) .gt. 1.E-4) RERRZC=abs(FC3/ZC3)
      if (abs(ZC3) .le. 1.E-4) RERRZC=abs(FC3)
C
      if ((RERRZA .lt. 1.E-6) .and. (RERRZB .lt. 1.E-6) .and.
     +    (RERRZC .lt. 1.E-6)) go to 550
C
  650 continue
C    ******************************
C    ***** End of inner loop *****
C    ******************************
C
      call GOTOXY(23,12)
      write(*,651) TIME
  651 format(1x,'Stiff Phase Current Characteristics at ',F8.7,
     +        ' seconds')
C
  550   TA=IMA*KT*BEMFA/KK3
        TB=IMB*KT*BEMFB/KK3
        TC=IMC*KT*BEMFC/KK3
        TM=TA+TB+TC
        call TCONST(ICTMF,TM,.005,NTIME,NTIM47,DELTIM,TMF)
        TMM=KT*IM
        TBM=BM*WM
        VKBWM=KB*WM
C
        if (WM .lt. 0.0) go to 180
          TN1=TM-TL
          go to 185
  180     TN1=TM+TL
  185     continue
        TN2=TN1/B
C
        WM1=WM
        THETA1=THETA
        call TCONST(WM0,TN2,A2,NTIME,NTIM48,DELTIM,WM)
        call INTGRL(NTIME,NTIM23,DELTIM,THETA0,PREV7,WM,CURV7,
     +             HOLD3,PTHETA)
C
        THETA=PTHETA
        F3=THETA-THETA1
C     *********************************************
C     ***** MODIFIED LINEAR INTERPOLATION *****
C     *********************************************
C
      if (NTIME .eq. 1) go to 601
C
      if (NUMIT .eq. 1) then
        X1=X3
        F1=F3
        X3=THETA
        go to 500
      elseif (NUMIT .eq. 2) then
        X2=X3
        F2=F3
        if (abs(F2-F1) .eq. 0.) F2=.5*F2+1.E-6
        if (abs(F2-F1) .ne. 0.) X3=X2-F2*(X2-X1)/(F2-F1)
        TSIGN=F3
        go to 500
      elseif (F3 .ne. 0.) then
        if (F1*F2 .lt. 0.) then
           if (F1*F3 .lt. 0.) then
              X2=X3
              F2=F3
              if (F3*TSIGN .gt. 0.) F1=F1/2.
              X3=X2-F2*(X2-X1)/(F2-F1)
           elseif (F1*F3 .gt. 0.) then
              X1=X3
              F1=F3
              if (F3*TSIGN .gt. 0.) F2=F2/2.
              X3=X2-F2*(X2-X1)/(F2-F1)
           endif
        elseif (F1*F2 .gt. 0.) then
C ...Cautious forward iteration using halving and checking scheme in
C     unbracketed region.
           if (HALF .eq. 0) then
               X1=X2
               X2=X3
               F1=F2
               F2=F3
              X3=X1+(X2-X1)/2.
              HALF=1
          elseif (HALF .eq. 1) then
              if (F1*F3 .lt. 0.) then
                HALF=0
                X2=X3
                F2=F3
                X3=X2-F2*(X2-X1)/(F2-F1)
              elseif (F1*F3 .gt. 0.) then
                HALF=0
                X1=X2
                X2=X3
                F1=F2
                F2=F3
                if (abs(F2-F1) .eq. 0.) F2=F2/2.
                if (abs(F2-F1) .ne. 0.) X3=X2-F2*(X2-X1)/(F2-F1)
              endif
          endif
       elseif (F1*F2 .eq. 0.) then
          X1=X2
          X2=X3
          F1=F2
          F2=F3
          if (abs(F2-F1) .eq. 0.) F2=F2/2.
          if (abs(F2-F1) .ne. 0.) X3=X2-F2*(X2-X1)/(F2-F1)
       endif
      endif
C
      if (abs(X3) .gt. 1.E-4) RELERR=abs(F3/X3)
      if (abs(X3) .le. 1.E-4) RELERR=abs(F3)
C
      if (RELERR .lt. 1.E-6) go to 601
  500 continue
      call GOTOXY(24,15)
      write(*,652) TIME
  652 format(1x,'FAILED Convergence of Outer Loop at ',F8.7, ' seconds')
C
  601 WMRPM=WM*30./PI
      THDEG=THETA*180.0/PI
      X3=THETA+WM*DELTIM
      THETAF=REDRAT*THETA*180./PI
      OMEGAF=REDRAT*WM*180./PI
      PREIMA=ZA3+.5*DIADT*DELTIM
      PREIMB=ZB3+.5*DIBDT*DELTIM
      PREIMC=ZC3+.5*DICDT*DELTIM
      ZA3=PREIMA
      ZB3=PREIMB
      ZC3=PREIMC
      DIRM1=DIR
C
C    ***************************
```

```
C    ***** End outer loop *****
C    **************************
C
C  ... Generate Plotting Arrays ...
      if (TIME .ge. BEGTIM) then
        NCTR=NCTR+1
        if ((mod(NCTR,SIM2PL) .eq. 0) .or. (NCTR .eq. 1)) then
          NPTS=NPTS+1
C  ...  Output data to file for future retrieval and plotting ...
C
          XTIME(NPTS)=TIME
C
          write(4,1200) TIME,THETAF,ORDER,OMEGAF,NODE,PLUG
          write(5,1210) IM,IMA,IMB,IMC,TM,TMF
          write(6,1220) VD1D,VD2D,VD3D,VD4D,VD5D,VD6D
          write(7,1230) SW1,SW2,SW3,SW4,SW5,SW6
 1200     format(5F15.7,3X,I3)
 1210     format(6F15.7)
 1220     format(6F15.7)
 1230     format(6F5.2)
        endif
      endif
C
  100 CONTINUE
      close(4,STATUS='KEEP')
      close(5,STATUS='KEEP')
      close(6,STATUS='KEEP')
      close(7,STATUS='KEEP')
C
C     ******************************
C     ***** Plotting selection *****
C     ******************************
C
C *** Clear Screen & Home Cursor ***
  400 call CLRSCR
C
      write(*,1305)
      read(*,'(A)') DISOPT
C
      if ((DISOPT .eq. 'm') .or. (DISOPT .eq. 'M')) then
        MODEL=99
        IOPORT=99
      elseif ((DISOPT .eq. 'p') .or. (DISOPT .eq. 'P')) then
        MODEL=PMODEL
        IOPORT=1
C  ... Ioport=9600 is COM1 ...
C  ... Ioport=9650 is COM2 ...
        if ((MODEL .eq. 20) .or. (MODEL .eq. 30)) IOPORT=9650
      elseif ((DISOPT .eq. 'r') .or. (DISOPT .eq. 'R')) then
        GO TO 13
      elseif ((DISOPT .eq. 'w') .or. (DISOPT .eq. 'W')) then
```

```
C
C     *********************************************
C     ***** Output Simulation Specs to Printer ***
C     *********************************************
C
      call PRNOUT(BEGTIM,FINTIM,PTSPLT,MAXITS,SIM2PL,DELTIM,NTERMS,
     +            E0,EDOT0,TYPE,STPMAG,RSLOPE,SINAMP,SINFRQ,SINPHA,
     +            NLCHAR,DBAND,PERIOD,KPWM,RIN,ROUT,RDADJ,KTM,KBM,
     +            KV,KP,RA,LA,BM,BL,JM,JL,RSAT,RCUT,TTIME,RS,THADV,
     +            TDPLUG)
C
          go to 400
C
      elseif ((DISOPT .eq. 's') .or. (DISOPT .eq. 'S')) then
C
C     *****************************************
C     *** OPEN/WRITE/CLOSE INPUT DATA FILE ***
C     *****************************************
C
        open(2,FILE='MOTOR.INP',STATUS='OLD',ACCESS='SEQUENTIAL')
           write(2,1000) PMODEL,PRTCHR,RIN,ROUT,RDADJ
           write(2,1020) BEGTIM,FINTIM,PTSPLT,MAXITS,SIM2PL
           write(2,1022) KPWM,KV,E0,EDOT0,TTIME,XORG,YORG
           write(2,1024) RS,RSAT,JL,BL,KTM
           write(2,1026) JM,RA,LA,KBM,THADV,TDPLUG
           write(2,1028) BM,KP,PERIOD,DBAND,KA
           write(2,1030) TYPE,RCUT,STPMAG,RSLOPE
           write(2,1032) SINAMP,SINFRQ,SINPHA,DRIVE
        close(2,STATUS='KEEP')
C
          go to 400
C
      elseif ((DISOPT .eq. 'Q') .or. (DISOPT .eq. 'q')) then
        GO TO 460
      else
        go to 400
      end if
C
      call DISPLA(XORG,YORG,DISOPT,PRTCHR,ELEMNT,DRIVE,XTIME)
C
      go to 400
  460 continue
C
C  ***  I/O Statements  ***
C
    4 format(//////,25X,'*** BRUSHLESS DC MOTOR SIMULATION ***',//,
     +              25X,'         Vincent S. Rossitto',/,
     +              25x,'      Naval Postgraduate School',//////)
C
    5 format(32X,'*** MAIN MENU ***',//,
     +       20X,'[H]----> HARDWARE Configuration Menu',/,
     +       20X,'[M]----> MOTOR Parameter Menu',/,
     +       20X,'[N]----> NON-LINEAR Element Selection Menu',/,
     +       20X,'[O]----> OPTIONS for Simulation',/,
     +       20X,'[C]----> COMMAND Input Selection Menu',/,
     +       20X,'[S]----> SAVE All Changes',/,
     +       20X,'[R]----> RUN Simulation Program',/,
     +       20X,'[Q]----> QUIT the Program',//,
     +        8X,'ENTER SELECTION---->',\)
C
 105    format(30X,'*** HARDWARE MENU ***',//,
     +       20X,'[P]----> PRINTER/PLOTTER configuration change',/,
     +       20X,'[Q]----> QUIT THIS MENU',//,
     +        8X,'ENTER SELECTION---->',\)
 1000 format(1X,I3,2X,A51,2X,3F15.7)
 1020 format(1X,4F15.7,1X,I3)
 1022 format(1X,7F15.7)
 1024 format(1X,5F15.7)
 1026 format(1X,6F15.7)
 1028 format(1X,5F15.7)
 1030 format(1X,A15,3F15.7)
 1032 format(1X,3F15.7,1X,A3)
 2000 format(1X,'END OF FILE')
C
 240  format(12X,'*** SIMULATION OPTIONS MENU ***',//,
     + 1X,F15.7,1X,'[BEGTIM]  Start Time of Plotting Window',/,
     + 1X,F15.7,1X,'[FINTIM]  Stop Time of Plotting Window',/,
     + 1X,F15.7,1X,'[PTSPLT]  Points to be Plotted per Curve',/,
     + 1X,F15.7,1X,'[MAXITS]  Max Number of Simulation Iterations',/,
     + 13X,I3,1X,  '[SIM2PL]  Ratio: Points Simulated/Plotted',/,
     + 1X,F15.7,1X,'[E0]      Initial Fin Position ERROR (deg)',/,
     + 1X,F15.7,1X,'[EDOT0]   Initial Fin Velocity ERROR (deg/s)',/,
     + 1X,F15.7,1X,'[XORG]    X Coordinate of Plotting Origin',/,
     + 1X,F15.7,1X,'[YORG]    Y Coordinate of Plotting Origin',/,
     + 13X,A3,1X,  '[DRIVE]   Drive (d:) for Virtual Memory',/,
     + 17X,'[Q]       QUIT THIS MENU',///,
     + 15X,'Computed simulation step size ---> ',F9.8, 'seconds',/,
     + 15X,'Computed total number of steps---> ',I6,//,
     + 1X,'Enter variable name (UPPERCASE) or Q to QUIT ---> ',\)
C
 245  format(12X,'*** COMMAND INPUT SELECTION MENU ***',//,
     + 1X,A15,1X,'[TYPE]    STEP, RAMP, or SINE Response',/,
     + 1X,F15.7,1X,'[STPMAG]  Commanded Position for STEP Response',/,
     + 1X,F15.7,1X,'[RSLOPE]  Slope of RAMP Function',/,
     + 1X,F15.7,1X,'[SINAMP]  Amplitude of SINE Function',/,
     + 1X,F15.7,1X,'[SINFRQ]  Frequency (deg/sec) of SINE Function',/,
     + 1X,F15.7,1X,'[SINPHA]  Phase Angle (deg) of SINE Function',/,
     + 17X,'[Q]       QUIT THIS MENU',///,
     + 1X,'Enter variable name (UPPERCASE) or Q to QUIT ---> ',\)
C
 270  format(///,8X,'*** NON-LINEAR ELEMENT SELECTION ***',//,
     + 17X,        '[R]    Relay (Bang-Bang)',/,
     + 17X,         '[P]    Pulse Width Modulator',/,
     + 1X,F15.7,1X,'[KV]    Velocity Feedback Constant',/,
     + 1X,F15.7,1X,'[KP]    Position Feedback Constant',/,
     + 17X,         '[Q]    QUIT THIS MENU/RETURN TO MAIN MENU',//,
     + 1X,'Enter Selection ---> ',\)
C
 272  format(10X,'CURRENT SELECTION --> ',A30)
C
 280  format(///,8X,'*** SATURATING AMPLIFIER SPECIFICATIONS ***',//,
     + 1X,F15.7,1X,'[DBAND]   Deadband Applied to System Feedback',/,
     + 1X,F15.7,1X,'[KA]      Amplifier Gain',/,
     + 17X,'[Q]        QUIT THIS MENU',//,
     + 1X,'Enter the selection (UPPERCASE) ---> ',\)
C
 290  format(///,15X,'*** RELAY SPECIFICATIONS ***',//,
     + 1X,F15.7,1X,'[DBAND]   Deadband Applied to System Feedback',/,
     + 17X,'[Q]        QUIT THIS MENU',//,
     + 1X,'Enter the selection (UPPERCASE) ---> ',\)
C
 300  format(///,5X,'*** PULSE WIDTH MODULATOR SPECIFICATIONS ***',//,
     + 1X,F15.7,1X,'[DBAND]   Deadband Applied to System Feedback',/,
     + 1X,F15.7,1X,'[PERIOD]  Period of PWM Reference Cycle(sec)',/,
     + 1X,F15.7,1X,'[KPWM]    PWM Amplifier Gain',/,
     + 17X,'[Q]        QUIT THIS MENU',//,
     + 1X,'Enter the selection (UPPERCASE) ---> ',\)
C
 1305 FORMAT(/////,2X,'Display options:',/,
     +            5X,'[M] MONITOR',/,
     +            5X,'[P] PRINTER',/,
     +            5X,'[R] RETURN TO START-UP MENU (RE-INITIALIZE)',/,
     +            5X,'[W] WRITE SIMULATION SPECIFICATIONS TO PRINTER',/,
     +            5X,'[S] SAVE SIMULATION SPECIFICATIONS TO DISK',/,
     +            5X,'[Q] QUIT THE PROGRAM',//,
     +            2X,'Enter selection [M,P,R,W,S,Q] ---> ',\)
C
 1500 format(1X,I3,2X,A50)
      STOP
      END
------------------------------------------------------------
C     BLDCM2A.FOR  (subroutines PRNOPT,MOTPAR,DISPLA,PRNOUT)
C     These subroutines are compiled as a group, but separately from
C     BLDCM1 & BLDCM2A due to size limitations. Subroutines must be
C     linked together.
C
C                   Last Revision --> 04 April 1987
C                   LT Vincent S. Rossitto, USN
C
C    ******************************************
C    *** PRINTER/PLOTTER SELECTION MENU ***
C    ******************************************
C
```

```
C     Provides user interface for selection of Printer for output
C     device.
C
         subroutine PRNOPT(PMODEL,PRTSEL,PRTCHR)
            implicit REAL*4 (A-Z)
            integer*2 PMODEL
            character*6 PRTSEL
            character*51 PRTCHR
C
 131        call CLRSCR
            write(*,130)
            read(*,'(A)') PRTSEL
C
            if (PRTSEL .eq. '0') then
               PRTCHR='Epson FX-80 Printer, single density'
               PMODEL=0
            elseif (PRTSEL .eq. '1') then
               PRTCHR='Epson FX-80 Printer, double density'
               PMODEL=1
            elseif (PRTSEL .eq. '2') then
               PRTCHR='Epson FX-80 Printer, dble spd,dual density'
               PMODEL=2
            elseif (PRTSEL .eq. '3') then
               PRTCHR='Epson FX-80 Printer, quad density'
               PMODEL=3
            elseif (PRTSEL .eq. '4') then
               PRTCHR='Epson FX-80 Printer, CRT Graphics I'
               PMODEL=4
            elseif (PRTSEL .eq. '5') then
               PRTCHR='Epson FX-80 Printer, plotter graphics'
               PMODEL=5
            elseif (PRTSEL .eq. '6') then
               PRTCHR='Epson FX-80 Printer, CRT Graphics II'
               PMODEL=6
            elseif (PRTSEL .eq. '10') then
               PRTCHR='Epson FX-100 Printer, single density'
               PMODEL=7
            elseif (PRTSEL .eq. '11') then
               PRTCHR='Epson FX-100 Printer, double density'
               PMODEL=11
            elseif (PRTSEL .eq. '12') then
               PRTCHR='Epson FX-100 Printer, dble spd,dual density'
               PMODEL=12
            elseif (PRTSEL .eq. '13') then
               PRTCHR='Epson FX-100 Printer, quad density'
               PMODEL=13
            elseif (PRTSEL .eq. '14') then
               PRTCHR='Epson FX-100 Printer, CRT Graphics I'
               PMODEL=14
            elseif (PRTSEL .eq. '15') then
               PRTCHR='Epson FX-100 Printer, plotter graphics'
```

```
                  PMODEL=15
               elseif (PRTSEL .eq. '16') then
                  PRTCHR='Epson FX-100 Printer, CRT Graphics II'
                  PMODEL=16
               elseif (PRTSEL .eq. '20') then
                  PRTCHR='HP 7470A Graphics Plotter'
                  PMODEL=20
               elseif (PRTSEL .eq. '30') then
                  PRTCHR='HP 7475A Graphics Plotter'
                  PMODEL=30
               elseif (PRTSEL .eq. '60') then
                  PRTCHR='HP 2686A Laser Jet Printer'
                  PMODEL=60
C
C  ... Quit the Printer Menu ...
               elseif ((PRTSEL .eq. 'Q') .or. (PRTSEL .eq. 'q')) then
                  go to 101
               else
                  go to 131
               endif
 101           continue
C
 130  FORMAT(24X,'*** PRINTER OPTIONS MENU ***',//,
     +  15X,'[0] --> Epson FX-80 Printer, single density',/,
     +  15X,'[1] --> Epson FX-80 Printer, double density',/,
     +  15X,'[2] --> Epson FX-80 Printer, dble spd,dual density',/,
     +  15X,'[3] --> Epson FX-80 Printer, quad density',/,
     +  15X,'[4] --> Epson FX-80 Printer, CRT Graphics I',/,
     +  15X,'[5] --> Epson FX-80 Printer, plotter graphics',/,
     +  15X,'[6] --> Epson FX-80 Printer, CRT Graphics II',/,
     +  15X,'[10] -> Epson FX-100 Printer, single density',/,
     +  15X,'[11] -> Epson FX-100 Printer, double density',/,
     +  15X,'[12] -> Epson FX-100 Printer, dble spd,dual density',/,
     +  15X,'[13] -> Epson FX-100 Printer, quad density',/,
     +  15X,'[14] -> Epson FX-100 Printer, CRT Graphics I',/,
     +  15X,'[15] -> Epson FX-100 Printer, plotter graphics',/,
     +  15X,'[16] -> Epson FX-100 Printer, CRT Graphics II',/,
     +  15X,'[20] -> HP 7470A Graphics Plotter',/,
     +  15X,'[30] -> HP 7475A Graphics Plotter',/,
     +  15X,'[60] -> HP 2686A Laser Jet Printer (NPS installation)',/,
     +  15X,'[Q] -->   QUIT THIS MENU',//,
     +  3X,'Enter Printer Selection Integer or Q to QUIT ---> ',\)
               return
               end
C.................................................................
C   ********************************************
C   **** Motor Parameter Input Subroutine ***
C   ********************************************
C
        subroutine MOTPAR(KTM,KBM,RIN,ROUT,RDADJ,RA,LA,BM,BL,JM,JL,
     +                    RSAT,RCUT,TTIME,RS,THADV,TDPLUG)
```

```
      implicit REAL(A-Z)
      character*6 ANS21
C
 201  call CLRSCR
      write(*,230) KTM,KBM,RIN,ROUT,RDADJ,RA,LA,BM,BL,JM,JL,
     +             RSAT,RCUT,TTIME,RS,THADV,TDPLUG
      read(*,'(A)') ANS21
C
      if (ANS21 .eq. 'KTM') then
         call GOTOXY(24,1)
         write(*,'(A\)')'Enter a REAL value for KTM--> '
         read(*,*) KTM
         go to 201
      elseif (ANS21 .eq. 'KBM') then
         call GOTOXY(24,1)
         write(*,'(A\)')'Enter a REAL value for KBM--> '
         read(*,*) KBM
         go to 201
      elseif (ANS21 .eq. 'RIN') then
         call GOTOXY(24,1)
         write(*,'(A\)')'Enter a REAL value for RIN--> '
         read(*,*) RIN
         go to 201
      elseif (ANS21 .eq. 'ROUT') then
         call GOTOXY(24,1)
         write(*,'(A\)')'Enter a REAL value for ROUT--> '
         read(*,*) ROUT
         go to 201
      elseif (ANS21 .eq. 'RDADJ') then
         call GOTOXY(24,1)
         write(*,'(A\)')'Enter a REAL value for RDADJ--> '
         read(*,*) RDADJ
         go to 201
      elseif (ANS21 .eq. 'RA') then
         call GOTOXY(24,1)
         write(*,'(A\)')'Enter a REAL value for RA--> '
         read(*,*) RA
         go to 201
      elseif (ANS21 .eq. 'LA') then
         call GOTOXY(24,1)
         write(*,'(A\)')'Enter a REAL value for LA--> '
         read(*,*) LA
         go to 201
      elseif (ANS21 .eq. 'BM') then
         call GOTOXY(24,1)
         write(*,'(A\)')'Enter a REAL value for BM--> '
         read(*,*) BM
         go to 201
      elseif (ANS21 .eq. 'BL') then
         call GOTOXY(24,1)
         write(*,'(A\)')'Enter a REAL value for BL--> '
```

```
            read(*,*) BL
            go to 201
         elseif (ANS21 .eq. 'JM') then
            call GOTOXY(24,1)
         write(*,'(A\)')'Enter a REAL value for JM--> '
            read(*,*) JM
            go to 201
         elseif (ANS21 .eq. 'JL') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for JL--> '
            read(*,*) JL
            go to 201
         elseif (ANS21 .eq. 'RSAT') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for RSAT--> '
            read(*,*) RSAT
            go to 201
         elseif (ANS21 .eq. 'RCUT') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for RCUT--> '
            read(*,*) RCUT
            go to 201
         elseif (ANS21 .eq. 'TTIME') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for TTIME--> '
            read(*,*) TTIME
            go to 201
         elseif (ANS21 .eq. 'RS') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for RS--> '
            read(*,*) RS
            go to 201
         elseif (ANS21 .eq. 'THADV') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for THADV--> '
            read(*,*) THADV
            go to 201
         elseif (ANS21 .eq. 'TDPLUG') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for TDPLUG--> '
            read(*,*) TDPLUG
            go to 201
C ... Quit Motor Parameters Menu ...
         elseif (ANS21 .eq. 'Q') then
            go to 1
         else
            go to 201
         end if
  1      continue
C
 230  format(10X,'MOTOR PARAMETER SELECTION MENU',//,
     + 1X,F15.7,1X,'[KTM]      Motor Torque Constant',/,
     + 1X,F15.7,1X,'[KBM]      Motor Back EMF Constant',/,
     + 1X,F15.7,1X,'[RIN]      Current Limiting Resistance (inside)',/,
     + 1X,F15.7,1X,'[ROUT]     Current Limiting Resistance (outside)',/,
     + 1X,F15.7,1X,'[RDADJ]    Series R Added to Freewheeling Diodes',/,
     + 1X,F15.7,1X,'[RA]       Motor Phase Resistance(Ohm)',/,
     + 1X,F15.7,1X,'[LA]       Motor Phase Inductance(Henries)',/,
     + 1X,F15.7,1X,'[BM]       Motor Viscous Friction Coeff',/,
     + 1X,F15.7,1X,'[BL]       Load Viscous Friction Coeff',/,
     + 1X,F15.7,1X,'[JM]       Motor Inertia(oz-in/s^2)',/,
     + 1X,F15.7,1X,'[JL]       Load Inertia(oz-in/s^2)',/,
     + 1X,F15.7,1X,'[RSAT]     Equiv Ckt Resistance of Trans Satur',/,
     + 1X,F15.7,1X,'[RCUT]     Equiv Ckt Resistance of Trans Cutoff',/,
     + 1X,F15.7,1X,'[TTIME]    Transistor Switching Time',/,
     + 1X,F15.7,1X,'[RS]       Internal Resist of Supply Voltage',/,
     + 1X,F15.7,1X,'[THADV]    Commutation Advance (Electrical Deg)',/,
     + 1X,F15.7,1X,'[TDPLUG]   Commutation Dead Time while Plugging',/,
     + 10X,'[Q]        QUIT THIS MENU',//,
     + 1X,'Enter Variable Name(UPPERCASE) or Q to QUIT ---> ',\)
C
         return
         end
C.................................................................
C    ****************************************
C    *** GRAPHIC OUTPUT SELECTION MENU ***
C    ****************************************
C
C     Provides user selection for graphic output of data.
C
C
      subroutine DISPLA(XORG,YORG,DISOPT,PRTCHR,ELEMNT,DRIVE,XTIME)
         implicit real*4 (A-Z)
         common BEGTIM,FINTIM,NPTS,IOPORT,MODEL,XLEN,YLEN,PLEN,PLEN1,
     +          XTITLE,YTITLE,PTITLE,PTIT1
         real*4 XTIME(1010),Y1(1010),Y2(1010)
         integer*2 NPTS,PCTR,XLEN,YLEN,IOPORT,MODEL,ELEMNT
         character*3 DISOPT,PLOPT,DRIVE
         character*25 XTITLE,YTITLE
         character*51 PRTCHR,PTITLE,PTIT1
C
C *** Clear Screen & Home Cursor ***
  410 call CLRSCR
      if ((DISOPT .eq. 'p') .or. (DISOPT .eq. 'P')) then
        call GOTOXY(24,20)
        write(*,*) PRTCHR
        call GOTOXY(1,1)
      endif
      write(*,1300)
      read(*,'(A)') PLOPT
C
      if ((PLOPT .eq. 'Q') .or. (PLOPT .eq. 'q')) then
```

```
          go to 400
        elseif (PLOPT .eq. '1') then
              XTITLE='TIME (seconds)'
              XLEN=-15
              YTITLE='FIN POSITION (deg)'
              YLEN=19
           if (ELEMNT .eq. 1) then
              PTITLE='FIN POSITION RESPONSE WITH RELAY CONTROLLER'
              PLEN=44.
           elseif (ELEMNT .eq. 3) then
              PTITLE='FIN POSITION RESPONSE WITH PWM CONTROLLER'
              PLEN=42.
           endif
           PTIT1='BRUSHLESS DC MOTOR'
           PLEN1=20.
C
C  ... Data Retrieval ...
           if (DRIVE .eq. 'A') then
             open(4,file='a:BLDCM1.VIR',status='OLD',access='SEQUENTIAL')
           elseif (DRIVE .eq. 'B') then
             open(4,file='b:BLDCM1.VIR',status='OLD',access='SEQUENTIAL')
           elseif (DRIVE .eq. 'C') then
             open(4,file='c:BLDCM1.VIR',status='OLD',access='SEQUENTIAL')
           endif
              do 830 PCTR=1,NPTS
                  read(4,930) THETAF,ORDER
  930             format(15x,2F15.7)
                  Y1(PCTR)=THETAF
                  Y2(PCTR)=ORDER
  830         continue
           close(4,status='KEEP')
C
           call MGRAPH(XTIME,Y1,Y2,XORG,YORG,DISOPT)
C
        elseif (PLOPT .eq. '2') then
              XTITLE='TIME (seconds)'
              XLEN=-15
              YTITLE='FIN VELOCITY (deg/sec)'
              YLEN=23
           if (ELEMNT .eq. 1) then
              PTITLE='FIN VELOCITY RESPONSE WITH RELAY CONTROLLER'
              PLEN=44.
           elseif (ELEMNT .eq. 3) then
              PTITLE='FIN VELOCITY RESPONSE WITH PWM CONTROLLER'
              PLEN=42.
           endif
           PTIT1='BRUSHLESS DC MOTOR'
           PLEN1=20.
C
C  ... Data Retrieval ...
           if (DRIVE .eq. 'A') then
```

```
             open(4,file='a:BLDCM1.VIR',status='OLD',access='SEQUENTIAL')
           elseif (DRIVE .eq. 'B') then
             open(4,file='b:BLDCM1.VIR',status='OLD',access='SEQUENTIAL')
           elseif (DRIVE .eq. 'C') then
             open(4,file='c:BLDCM1.VIR',status='OLD',access='SEQUENTIAL')
           endif
              do 832 PCTR=1,NPTS
                  read(4,932) OMEGAF
                  Y1(PCTR)=OMEGAF
  832         continue
  932         format(45X,F15.7)
           close(4,status='KEEP')
C
           call GRAPH(XTIME,Y1,XORG,YORG,DISOPT)
C
        elseif (PLOPT .eq. '3') then
              XTITLE='TIME (seconds)'
              XLEN=-15
              YTITLE='IM (amps)'
              YLEN=10
           if (ELEMNT .eq. 1) then
              PTITLE='MOTOR SOURCE CURRENT WITH RELAY CONTROLLER'
              PLEN=43.
           elseif (ELEMNT .eq. 3) then
              PTITLE='MOTOR SOURCE CURRENT WITH PWM CONTROLLER'
              PLEN=41.
           endif
           PTIT1='BRUSHLESS DC MOTOR'
           PLEN1=20.
C
C  ... Data Retrieval ...
           if (DRIVE .eq. 'A') then
             open(5,file='a:BLDCM2.VIR',status='OLD',access='SEQUENTIAL')
           elseif (DRIVE .eq. 'B') then
             open(5,file='b:BLDCM2.VIR',status='OLD',access='SEQUENTIAL')
           elseif (DRIVE .eq. 'C') then
             open(5,file='c:BLDCM2.VIR',status='OLD',access='SEQUENTIAL')
           endif
              do 833 PCTR=1,NPTS
                  read(5,933) IM
                  Y1(PCTR)=IM
  833         continue
  933         format(F15.7)
           close(5,status='KEEP')
C
           call GRAPH(XTIME,Y1,XORG,YORG,DISOPT)
C
        elseif (PLOPT .eq. '4') then
              XTITLE='TIME (seconds)'
              XLEN=-15
              YTITLE='IMA (amps)'
```

```
            YLEN=11
         if (ELEMNT .eq. 1) then
            PTITLE='MOTOR PHASE A CURRENT WITH RELAY CONTROLLER'
            PLEN=44.
         elseif (ELEMNT .eq. 3) then
            PTITLE='MOTOR PHASE A CURRENT WITH PWM CONTROLLER'
            PLEN=42.
         endif
         PTIT1='BRUSHLESS DC MOTOR'
         PLEN1=20.
C
C  ... Data Retrieval ...
         if (DRIVE .eq. 'A') then
           open(5,file='a:BLDCM2.VIR',status='OLD',access='SEQUENTIAL')
         elseif (DRIVE .eq. 'B') then
           open(5,file='b:BLDCM2.VIR',status='OLD',access='SEQUENTIAL')
         elseif (DRIVE .eq. 'C') then
           open(5,file='c:BLDCM2.VIR',status='OLD',access='SEQUENTIAL')
         endif
            do 834 PCTR=1,NPTS
                read(5,934) IMA
                Y1(PCTR)=IMA
  834       continue
  934       format(15X,F15.7)
         close(5,status='KEEP')
C
         call GRAPH(XTIME,Y1,XORG,YORG,DISOPT)
C
      elseif (PLOPT .eq. '5') then
            XTITLE='TIME (seconds)'
            XLEN=-15
            YTITLE='IMB (amps)'
            YLEN=11
         if (ELEMNT .eq. 1) then
            PTITLE='MOTOR PHASE B CURRENT WITH RELAY CONTROLLER'
            PLEN=44.
         elseif (ELEMNT .eq. 3) then
            PTITLE='MOTOR PHASE B CURRENT WITH PWM CONTROLLER'
            PLEN=42.
         endif
         PTIT1='BRUSHLESS DC MOTOR'
         PLEN1=20.
C
C  ... Data Retrieval ...
         if (DRIVE .eq. 'A') then
           open(5,file='a:BLDCM2.VIR',status='OLD',access='SEQUENTIAL')
         elseif (DRIVE .eq. 'B') then
           open(5,file='b:BLDCM2.VIR',status='OLD',access='SEQUENTIAL')
         elseif (DRIVE .eq. 'C') then
           open(5,file='c:BLDCM2.VIR',status='OLD',access='SEQUENTIAL')
         endif
```

```
          do 835 PCTR=1,NPTS
             read(5,935) IMB
             Y1(PCTR)=IMB
 835      continue
 935      format(30X,F15.7)
       close(5,status='KEEP')
C
       call GRAPH(XTIME,Y1,XORG,YORG,DISOPT)
C
    elseif (PLOPT .eq. '6') then
          XTITLE='TIME (seconds)'
          XLEN=-15
          YTITLE='IMC (amps)'
          YLEN=11
       if (ELEMNT .eq. 1) then
          PTITLE='MOTOR PHASE C CURRENT WITH RELAY CONTROLLER'
          PLEN=44.
       elseif (ELEMNT .eq. 3) then
          PTITLE='MOTOR PHASE C CURRENT WITH PWM CONTROLLER'
          PLEN=42.
       endif
       PTIT1='BRUSHLESS DC MOTOR'
       PLEN1=20.
C
C  ... Data Retrieval ...
       if (DRIVE .eq. 'A') then
         open(5,file='a:BLDCM2.VIR',status='OLD',access='SEQUENTIAL')
       elseif (DRIVE .eq. 'B') then
         open(5,file='b:BLDCM2.VIR',status='OLD',access='SEQUENTIAL')
       elseif (DRIVE .eq. 'C') then
         open(5,file='c:BLDCM2.VIR',status='OLD',access='SEQUENTIAL')
       endif
          do 836 PCTR=1,NPTS
             read(5,936) IMC
             Y1(PCTR)=IMC
 836      continue
 936      format(45X,F15.7)
       close(5,status='KEEP')
C
       call GRAPH(XTIME,Y1,XORG,YORG,DISOPT)
C
    elseif (PLOPT .eq. '7') then
          XTITLE='TIME (seconds)'
          XLEN=-15
          YTITLE='TM (oz-in)'
          YLEN=11
       if (ELEMNT .eq. 1) then
          PTITLE='MOTOR TORQUE (oz-in) WITH RELAY CONTROLLER'
          PLEN=43.
       elseif (ELEMNT .eq. 3) then
          PTITLE='MOTOR TORQUE (oz-in) WITH PWM CONTROLLER'
```

```
            PLEN=41.
         endif
         PTIT1='BRUSHLESS DC MOTOR'
         PLEN1=20.
C
C  ... Data Retrieval ...
         if (DRIVE .eq. 'A') then
           open(5,file='a:BLDCM2.VIR',status='OLD',access='SEQUENTIAL')
         elseif (DRIVE .eq. 'B') then
           open(5,file='b:BLDCM2.VIR',status='OLD',access='SEQUENTIAL')
         elseif (DRIVE .eq. 'C') then
           open(5,file='c:BLDCM2.VIR',status='OLD',access='SEQUENTIAL')
         endif
            do 837 PCTR=1,NPTS
                read(5,937) TM
                Y1(PCTR)=TM
  837       continue
  937       format(60X,F15.7)
         close(5,status='KEEP')
C
         call GRAPH(XTIME,Y1,XORG,YORG,DISOPT)
C
      elseif (PLOPT .eq. '8') then
            XTITLE='TIME (seconds)'
            XLEN=-15
            YTITLE='TMF (oz-in)'
            YLEN=12
         if (ELEMNT .eq. 1) then
            PTITLE='FILTERED MOTOR TORQUE (oz-in) WITH RELAY CONTROLLER'
            PLEN=51.
         elseif (ELEMNT .eq. 3) then
            PTITLE='FILTERED MOTOR TORQUE (oz-in) WITH PWM CONTROLLER'
            PLEN=50.
         endif
         PTIT1='BRUSHLESS DC MOTOR'
         PLEN1=20.
C
C  ... Data Retrieval ...
         if (DRIVE .eq. 'A') then
           open(5,file='a:BLDCM2.VIR',status='OLD',access='SEQUENTIAL')
         elseif (DRIVE .eq. 'B') then
           open(5,file='b:BLDCM2.VIR',status='OLD',access='SEQUENTIAL')
         elseif (DRIVE .eq. 'C') then
           open(5,file='c:BLDCM2.VIR',status='OLD',access='SEQUENTIAL')
         endif
            do 838 PCTR=1,NPTS
                read(5,938) TMF
                Y1(PCTR)=TMF
  838       continue
  938       format(75X,F15.7)
         close(5,status='KEEP')
```

```
C
         call GRAPH(XTIME,Y1,XORG,YORG,DISOPT)
C
      elseif (PLOPT .eq. '9') then
           XTITLE='TIME (seconds)'
           XLEN=-15
           YTITLE='VD1D (volts)'
           YLEN=13
         if (ELEMNT .eq. 1) then
           PTITLE='POWER TRANSISTOR #1 VOLTAGE DROP (RELAY)'
           PLEN=41.
         elseif (ELEMNT .eq. 3) then
           PTITLE='POWER TRANSISTOR #1 VOLTAGE DROP (PWM)'
           PLEN=39.
         endif
         PTIT1='BRUSHLESS DC MOTOR'
         PLEN1=20.
C
C  ... Data Retrieval ...
         if (DRIVE .eq. 'A') then
           open(6,file='a:BLDCM3.VIR',status='OLD',access='SEQUENTIAL')
         elseif (DRIVE .eq. 'B') then
           open(6,file='b:BLDCM3.VIR',status='OLD',access='SEQUENTIAL')
         elseif (DRIVE .eq. 'C') then
           open(6,file='c:BLDCM3.VIR',status='OLD',access='SEQUENTIAL')
         endif
           do 839 PCTR=1,NPTS
               read(6,939) VD1D
               Y1(PCTR)=VD1D
  839      continue
  939      format(F15.7)
         close(6,status='KEEP')
C
         call GRAPH(XTIME,Y1,XORG,YORG,DISOPT)
C
      elseif (PLOPT .eq. '10') then
           XTITLE='TIME (seconds)'
           XLEN=-15
           YTITLE='VD2D (volts)'
           YLEN=13
         if (ELEMNT .eq. 1) then
           PTITLE='POWER TRANSISTOR #2 VOLTAGE DROP (RELAY)'
           PLEN=41.
         elseif (ELEMNT .eq. 3) then
           PTITLE='POWER TRANSISTOR #2 VOLTAGE DROP (PWM)'
           PLEN=39.
         endif
         PTIT1='BRUSHLESS DC MOTOR'
         PLEN1=20.
C
C  ... Data Retrieval ...
```

```
         if (DRIVE .eq. 'A') then
           open(6,file='a:BLDCM3.VIR',status='OLD',access='SEQUENTIAL')
         elseif (DRIVE .eq. 'B') then
           open(6,file='b:BLDCM3.VIR',status='OLD',access='SEQUENTIAL')
         elseif (DRIVE .eq. 'C') then
           open(6,file='c:BLDCM3.VIR',status='OLD',access='SEQUENTIAL')
         endif
            do 840 PCTR=1,NPTS
                read(6,940) VD2D
                Y1(PCTR)=VD2D
 840        continue
 940        format(15X,F15.7)
         close(6,status='KEEP')
C
         call GRAPH(XTIME,Y1,XORG,YORG,DISOPT)
C
      elseif (PLOPT .eq. '11') then
            XTITLE='TIME (seconds)'
            XLEN=-15
            YTITLE='VD3D (volts)'
            YLEN=13
         if (ELEMNT .eq. 1) then
            PTITLE='POWER TRANSISTOR #3 VOLTAGE DROP (RELAY)'
            PLEN=41.
         elseif (ELEMNT .eq. 3) then
            PTITLE='POWER TRANSISTOR #3 VOLTAGE DROP (PWM)'
            PLEN=39.
         endif
         PTIT1='BRUSHLESS DC MOTOR'
         PLEN1=20.
C
C  ... Data Retrieval ...
         if (DRIVE .eq. 'A') then
           open(6,file='a:BLDCM3.VIR',status='OLD',access='SEQUENTIAL')
         elseif (DRIVE .eq. 'B') then
           open(6,file='b:BLDCM3.VIR',status='OLD',access='SEQUENTIAL')
         elseif (DRIVE .eq. 'C') then
           open(6,file='c:BLDCM3.VIR',status='OLD',access='SEQUENTIAL')
         endif
            do 841 PCTR=1,NPTS
                read(6,941) VD3D
                Y1(PCTR)=VD3D
 841        continue
 941        format(30X,F15.7)
         close(6,status='KEEP')
C
         call GRAPH(XTIME,Y1,XORG,YORG,DISOPT)
C
      elseif (PLOPT .eq. '12') then
            XTITLE='TIME (seconds)'
            XLEN=-15
            YTITLE='VD4D (volts)'
            YLEN=13
         if (ELEMNT .eq. 1) then
            PTITLE='POWER TRANSISTOR #4 VOLTAGE DROP (RELAY)'
            PLEN=41.
         elseif (ELEMNT .eq. 3) then
            PTITLE='POWER TRANSISTOR #4 VOLTAGE DROP (PWM)'
            PLEN=39.
         endif
         PTIT1='BRUSHLESS DC MOTOR'
         PLEN1=20.
C
C  ... Data Retrieval ...
         if (DRIVE .eq. 'A') then
           open(6,file='a:BLDCM3.VIR',status='OLD',access='SEQUENTIAL')
         elseif (DRIVE .eq. 'B') then
           open(6,file='b:BLDCM3.VIR',status='OLD',access='SEQUENTIAL')
         elseif (DRIVE .eq. 'C') then
           open(6,file='c:BLDCM3.VIR',status='OLD',access='SEQUENTIAL')
         endif
            do 842 PCTR=1,NPTS
                read(6,942) VD4D
                Y1(PCTR)=VD4D
 842        continue
 942        format(45X,F15.7)
         close(6,status='KEEP')
C
         call GRAPH(XTIME,Y1,XORG,YORG,DISOPT)
C
      elseif (PLOPT .eq. '13') then
            XTITLE='TIME (seconds)'
            XLEN=-15
            YTITLE='VD5D (volts)'
            YLEN=13
         if (ELEMNT .eq. 1) then
            PTITLE='POWER TRANSISTOR #5 VOLTAGE DROP (RELAY)'
            PLEN=41.
         elseif (ELEMNT .eq. 3) then
            PTITLE='POWER TRANSISTOR #5 VOLTAGE DROP (PWM)'
            PLEN=39.
         endif
         PTIT1='BRUSHLESS DC MOTOR'
         PLEN1=20.
C
C  ... Data Retrieval ...
         if (DRIVE .eq. 'A') then
           open(6,file='a:BLDCM3.VIR',status='OLD',access='SEQUENTIAL')
         elseif (DRIVE .eq. 'B') then
           open(6,file='b:BLDCM3.VIR',status='OLD',access='SEQUENTIAL')
         elseif (DRIVE .eq. 'C') then
           open(6,file='c:BLDCM3.VIR',status='OLD',access='SEQUENTIAL')
```

```
          endif
             do 843 PCTR=1,NPTS
                 read(6,943) VD5D
                 Y1(PCTR)=VD5D
  843        continue
  943        format(60X,F15.7)
          close(6,status='KEEP')
C
          call GRAPH(XTIME,Y1,XORG,YORG,DISOPT)
C
       elseif (PLOPT .eq. '14') then
             XTITLE='TIME (seconds)'
             XLEN=-15
             YTITLE='VD6D (volts)'
             YLEN=13
          if (ELEMNT .eq. 1) then
             PTITLE='POWER TRANSISTOR #6 VOLTAGE DROP (RELAY)'
             PLEN=41.
          elseif (ELEMNT .eq. 3) then
             PTITLE='POWER TRANSISTOR #6 VOLTAGE DROP (PWM)'
             PLEN=39.
          endif
          PTIT1='BRUSHLESS DC MOTOR'
          PLEN1=20.
C
C  ... Data Retrieval ...
          if (DRIVE .eq. 'A') then
            open(6,file='a:BLDCM3.VIR',status='OLD',access='SEQUENTIAL')
          elseif (DRIVE .eq. 'B') then
            open(6,file='b:BLDCM3.VIR',status='OLD',access='SEQUENTIAL')
          elseif (DRIVE .eq. 'C') then
            open(6,file='c:BLDCM3.VIR',status='OLD',access='SEQUENTIAL')
          endif
             do 844 PCTR=1,NPTS
                 read(6,944) VD6D
                 Y1(PCTR)=VD6D
  844        continue
  944        format(75X,F15.7)
          close(6,status='KEEP')
C
          call GRAPH(XTIME,Y1,XORG,YORG,DISOPT)
C
       elseif (PLOPT .eq. '15') then
             XTITLE='TIME (seconds)'
             XLEN=-15
             YTITLE='NODE O VOLTAGE (VDC)'
             YLEN=21
             PTITLE='CENTER CONNECTION VOLTAGE RESPONSE'
             PLEN=35.
             PTIT1='BRUSHLESS DC MOTOR'
             PLEN1=20.
```

```
C
C  ... Data Retrieval ...
         if (DRIVE .eq. 'A') then
           open(4,file='a:BLDCM1.VIR',status='OLD',access='SEQUENTIAL')
         elseif (DRIVE .eq. 'B') then
           open(4,file='b:BLDCM1.VIR',status='OLD',access='SEQUENTIAL')
         elseif (DRIVE .eq. 'C') then
           open(4,file='c:BLDCM1.VIR',status='OLD',access='SEQUENTIAL')
         endif
            do 845 PCTR=1,NPTS
                read(4,945) NODE
                Y1(PCTR)=NODE
 845        continue
 945        format(60X,F15.7)
         close(4,status='KEEP')
C
         call GRAPH(XTIME,Y1,XORG,YORG,DISOPT)
C
C
      else
        go to 410
      endif
C
 400  continue
C
1300  FORMAT(//,2X,'The following are plotting options',//,
     +          5X,' [1] FIN POSITION (THETAF)',/,
     +          5X,' [2] FIN VELOCITY (OMEGAF)',/,
     +          5X,' [3] MOTOR CURRENT (IM)',/,
     +          5X,' [4] MOTOR PHASE A CURRENT (IMA)',/,
     +          5X,' [5] MOTOR PHASE B CURRENT (IMB)',/,
     +          5X,' [6] MOTOR PHASE C CURRENT (IMC)',/,
     +          5X,' [7] MOTOR TORQUE (TM)',/,
     +          5X,' [8] FILTERED MOTOR TORQUE (TMF)',/,
     +          5X,' [9] POWER TRANSISTOR #1 VOLTAGE DROP (VD1D)',/,
     +          5X,'[10] POWER TRANSISTOR #2 VOLTAGE DROP (VD2D)',/,
     +          5X,'[11] POWER TRANSISTOR #3 VOLTAGE DROP (VD3D)',/,
     +          5X,'[12] POWER TRANSISTOR #4 VOLTAGE DROP (VD4D)',/,
     +          5X,'[13] POWER TRANSISTOR #5 VOLTAGE DROP (VD5D)',/,
     +          5X,'[14] POWER TRANSISTOR #6 VOLTAGE DROP (VD6D)',/,
     +          5X,'[15] REFERENCE NODE VOLTAGE RESPONSE (NODE)',/,
     +          5X,'[Q] QUIT THIS MENU',//,
     +          2X,'Enter selection [1-15,Q] ---> ',\)
C
      return
      end
C.................................................................
C     *************************************************
C     ***** Output Simulation Specs to Printer ***
C     *************************************************
C
```

```
C     Dumps simulation specifications to printer.
C
C
      subroutine PRNOUT(BEGTIM,FINTIM,PTSPLT,MAXITS,SIM2PL,DELTIM,
     +            NTERMS,E0,EDOT0,TYPE,STPMAG,RSLOPE,SINAMP,SINFRQ,
     +            SINPHA,NLCHAR,DBAND,PERIOD,KPWM,RIN,ROUT,RDADJ,
     +            KTM,KBM,KV,KP,RA,LA,BM,BL,JM,JL,RSAT,RCUT,TTIME,
     +            RS,THADV,TDPLUG)
      implicit REAL*4 (A-Z)
      integer*2 SIM2PL,NTERMS
      character*6 TYPE
      character*25 NLCHAR
C
C  ... Printer ready?? ...
         call CLRSCR
         call GOTOXY(12,25)
         write(*,*) 'Please ensure PRINTER is ready'
         call GOTOXY(20,1)
         PAUSE
C  ... Output Simulation Options to Printer ...
         open(8,file='prn',status='new')
C
         write(8,1600) BEGTIM,FINTIM,PTSPLT,MAXITS,SIM2PL,DELTIM,
     +                 NTERMS,E0,EDOT0
         write(8,1601) TYPE,STPMAG,RSLOPE,SINAMP,SINFRQ,SINPHA,
     +                 NLCHAR,DBAND,PERIOD,KPWM,RIN,ROUT,RDADJ
         write(8,1602) KTM,KBM,KV,KP,RA,LA,BM,BL,JM,JL,RSAT,
     +                 RCUT,TTIME,RS,THADV,TDPLUG
         write(8,1603)
C
 1600 format(/,18X,'*** BRUSHLESS DC MOTOR SIMULATION SPECS ***',/,
     + 1X,F15.7,1X,'[BEGTIM]  Start Time of Plotting Window',/,
     + 1X,F15.7,1X,'[FINTIM]  Stop Time of Plotting Window',/,
     + 1X,F15.7,1X,'[PTSPLT]  Points to be Plotted per Curve',/,
     + 1X,F15.7,1X,'[MAXITS]  Max Number of Simulation Iterations',/,
     + 13X,I3,1X,  '[SIM2PL]  Ratio: Points Simulated/Plotted',/,
     + 1X,F15.7,1X,'[DELTIM]  Simulation Step Size (seconds)',/,
     + 10X,I6,1X,  '[NTERMS]  Total Number of Simulation Steps',/,
     + 1X,F15.7,1X,'[E0]      Initial Fin Position ERROR (deg)',/,
     + 1X,F15.7,1X,'[EDOT0]   Initial Fin Velocity ERROR (deg/s)',//)
 1601 format(25X,'*** COMMAND INPUT SELECTION ***',/,
     + 1X,A15,1X,  '[TYPE]    STEP, RAMP, or SINE Response',/,
     + 1X,F15.7,1X,'[STPMAG]  Commanded Position for STEP Response',/,
     + 1X,F15.7,1X,'[RSLOPE]  Slope of RAMP Function',/,
     + 1X,F15.7,1X,'[SINAMP]  Amplitude of SINE Function',/,
     + 1X,F15.7,1X,'[SINFRQ]  Frequency (deg/sec) of SINE Function',/,
     + 1X,F15.7,1X,'[SINPHA]  Phase Angle (deg) of SINE Function',//,
     + 27X,'*** CONTROLLER SELECTION ***',/,
     + 10X,'CONTROLLER SELECTION --> ',A30,/,
     + 1X,F15.7,1X,'[DBAND]   Deadband Applied to System Feedback',/,
     + 1X,F15.7,1X,'[PERIOD]  Period of PWM Reference Cycle(sec)',/,
     + 1X,F15.7,1X,'[KPWM]     PWM Amplifier Gain',/,
     + 1X,F15.7,1X,'[RIN]      Current Limiting Resistance (inside)',/,
     + 1X,F15.7,1X,'[ROUT]     Current Limiting Resistance (outside)',/,
     + 1X,F15.7,1X,'[RDADJ]    Series R Added to Freewheeling Diodes',//)
 1602 format(25X,'*** MOTOR PARAMETER SELECTION ***',/,
     + 1X,F15.7,1X,'[KTM]      Motor Torque Constant',/,
     + 1X,F15.7,1X,'[KBM]      Motor Back EMF Constant',/,
     + 1X,F15.7,1X,'[KV]       Motor Velocity Feedback Constant',/,
     + 1X,F15.7,1X,'[KP]       Motor Position Feedback Constant',/,
     + 1X,F15.7,1X,'[RA]       Motor Phase Resistance(Ohm)',/,
     + 1X,F15.7,1X,'[LA]       Motor Phase Inductance(Henries)',/,
     + 1X,F15.7,1X,'[BM]       Motor Viscous Friction Coeff',/,
     + 1X,F15.7,1X,'[BL]       Load Viscous Friction Coeff',/,
     + 1X,F15.7,1X,'[JM]       Motor Inertia(oz-in/s^2)',/,
     + 1X,F15.7,1X,'[JL]       Load Inertia(oz-in/s^2)',/,
     + 1X,F15.7,1X,'[RSAT]     Equiv Ckt Resistance of Trans Satur',/,
     + 1X,F15.7,1X,'[RCUT]     Equiv Ckt Resistance of Trans Cutoff',/,
     + 1X,F15.7,1X,'[TTIME]    Transistor Switching Time',/,
     + 1X,F15.7,1X,'[RS]       Internal Resist of Supply Voltage',/,
     + 1X,F15.7,1X,'[THADV]    Commutation Advance (Electrical Deg)',/,
     + 1X,F15.7,1X,'[TDPLUG]   Commutation Dead Time while Plugging',/)
C
 1603    format('1')
         close(8,status='KEEP')
C
      return
      end
------------------------------------------------------------
C     BLDCM3A.FOR     (subroutines GRAPH,MGRAPH,PWMOD,RELAY,
C                       COMADV,HALL,TRANSW,LIMIT,FCNSW,STEP,DEADSP,
C                       RAMP,TCONST,DERIV,INTGRL,CLRSCR,GOTOXY)
C     These subroutines must be compiled as a group separately from
C     BLDCM1 because of compiler size limitations. BLDCM3A must be
C     linked to BLDCM1 & BLDCM2A at link time.
C
C                          Last Revision --> 04 April 1987
C                            LT Vincent S. Rossitto, USN
C
C  ********************************
C  ***** PLOTTING SUBROUTINES *****
C  *****(single function plot)*****
C  ********************************
      Subroutine GRAPH(X,Y,XORG,YORG,DISOPT)
C
      implicit REAL*4 (A-Z)
      COMMON BEGTIM,FINTIM,NPTS,IOPORT,MODEL,XLEN,YLEN,PLEN,PLEN1,
     +       XTITLE,YTITLE,PTITLE,PTIT1
      real*4 X(1010),Y(1010)
      integer*2 NPTS,IOPORT,MODEL,XLEN,YLEN,NCHAR,NCHAR1
      character*3 DISOPT,ANS
      character*25 XTITLE,YTITLE
      character*51 PTITLE,PTIT1
C
C ... Make a new title...
    5 call CLRSCR
      if ((DISOPT .eq. 'P') .or. (DISOPT .eq. 'p')) then
         call GOTOXY(8,30)
         write(*,*) 'Current Title is:'
         call GOTOXY(10,20)
         write(*,*) PTITLE
         call GOTOXY(11,20)
         write(*,*) PTIT1
         call GOTOXY(15,25)
         write(*,'(A\)') 'Do you want to change the title? '
         read(*,'(A)') ANS
         call CLRSCR
        if ((ANS .eq. 'Y') .or. (ANS .eq. 'y')) then
            call GOTOXY(5,10)
         write(*,*) 'Enter titles in left justified format'
            call GOTOXY(12,10)
         write(*,*) '12345678901234567890123456789012345678901234567890'
            call GOTOXY(13,10)
         write(*,*) '         1         2         3         4         5'
            call GOTOXY(15,25)
         write(*,*) '# of characters -->'
            call GOTOXY(20,10)
         write(*,*) '12345678901234567890123456789012345678901234567890'
            call GOTOXY(21,10)
         write(*,*) '         1         2         3         4         5'
            call GOTOXY(23,25)
         write(*,*) '# of characters -->'
            call GOTOXY(11,11)
         read(*,'(A51)') PTITLE
            call GOTOXY(15,46)
         read(*,*) PLEN
            call GOTOXY(19,11)
         read(*,'(A51)') PTIT1
            call GOTOXY(23,46)
         read(*,*) PLEN1
        elseif ((ANS .eq. 'N') .or. (ANS .eq. 'n')) then
            go to 10
        endif
         go to 5
      endif
C
   10 call GOTOXY(10,25)
      write(*,*) 'Calculating Plotting Data'
C
      ASPRAT=.65
      CHARHT=.22
      PTX=.5+(6.-PLEN*ASPRAT*CHARHT)/2.
      PTY=4.5
      PTX1=.5+(6.-PLEN1*ASPRAT*CHARHT)/2.
      PTY1=4.1
      NCHAR=ifix(PLEN)
      NCHAR1=ifix(PLEN1)
C
      call PLOTS(0,IOPORT,MODEL)
      call FACTOR(1.00)
      call ASPECT(ASPRAT)
C ... Draw a Border ...
      if ((DISOPT .eq. 'P') .or. (DISOPT .eq. 'p')) then
         call PLOT(XORG,YORG,-13)
         call PLOT(8.0,0.0,2)
         call PLOT(8.0,6.0,2)
         call PLOT(0.0,6.0,2)
         call PLOT(0.0,0.0,2)
      endif
C
C     call SCALE(X,6.,NPTS,1)
      call SCALE(Y,4.,NPTS,1)
      call STAXIS(.15,.22,.12,.080,3)
C  ... This scaling applies when the X axis represents Time...
      X(NPTS+1)=BEGTIM
      FIRSTX = X(NPTS+1)
      X(NPTS+2)=(X(NPTS)-X(NPTS+1))/6.
      DELTAX = X(NPTS+2)
      FIRSTY = Y(NPTS+1)
      DELTAY = Y(NPTS+2)
      call PLOT(1.25,1.,-13)
      call AXIS(0.0,0.0,XTITLE,XLEN,6.,0.,FIRSTX,DELTAX)
      call STAXIS(.15,.22,.12,.080,2)
      call AXIS(0.,0.,YTITLE,YLEN,4.,90.,FIRSTY,DELTAY)
      call SYMBOL(PTX,PTY,CHARHT,PTITLE,0.,NCHAR)
      call SYMBOL(PTX1,PTY1,CHARHT,PTIT1,0.,NCHAR1)
      call LINE(X,Y,NPTS,1,0,0)
      call PLOT(0.,0.,999)
C
      MODEL=99
      IOPORT=99
C
      return
      end
C
C  **********************************
C  ***** PLOTTING SUBROUTINES *****
C  ***** (multi-function plot)*****
C  **********************************
      Subroutine MGRAPH(X,Y,Z,XORG,YORG,DISOPT)
C
      implicit REAL*4 (A-Z)
      COMMON BEGTIM,FINTIM,NPTS,IOPORT,MODEL,XLEN,YLEN,PLEN,PLEN1,
     +       XTITLE,YTITLE,PTITLE,PTIT1
```

```
      real*4 X(1010),Y(1010),Z(1010)
      integer*2 NPTS,IOPORT,MODEL,XLEN,YLEN,NCHAR,NCHAR1
      character*3 DISOPT,ANS
      character*25 XTITLE,YTITLE
      character*51 PTITLE,PTIT1
C
      ASPRAT=.65
      CHARHT=.22
      CHARH1=.20
C
C ... Make a new title...
    5 call CLRSCR
      if ((DISOPT .eq. 'P') .or. (DISOPT .eq. 'p')) then
         call GOTOXY(8,30)
         write(*,*) 'Current Title is:'
         call GOTOXY(10,20)
         write(*,*) PTITLE
         call GOTOXY(11,20)
         write(*,*) PTIT1
         call GOTOXY(15,25)
         write(*,'(A\)') 'Do you want to change the title? '
         read(*,'(A)') ANS
         call CLRSCR
        if ((ANS .eq. 'Y') .or. (ANS .eq. 'y')) then
            call GOTOXY(5,10)
         write(*,*) 'Enter titles in left justified format'
            call GOTOXY(12,10)
         write(*,*) '12345678901234567890123456789012345678901234567890'
            call GOTOXY(13,10)
         write(*,*) '         1         2         3         4         5'
            call GOTOXY(15,25)
         write(*,*) '# of characters -->'
            call GOTOXY(20,10)
         write(*,*) '12345678901234567890123456789012345678901234567890'
            call GOTOXY(21,10)
         write(*,*) '         1         2         3         4         5'
            call GOTOXY(23,25)
         write(*,*) '# of characters -->'
            call GOTOXY(11,11)
         read(*,'(A51)') PTITLE
            call GOTOXY(15,46)
         read(*,*) PLEN
            call GOTOXY(19,11)
         read(*,'(A51)') PTIT1
            call GOTOXY(23,46)
         read(*,*) PLEN1
        elseif ((ANS .eq. 'N') .or. (ANS .eq. 'n')) then
            go to 10
        endif
         go to 5
      endif
```

```
C
   10 call GOTOXY(10,25)
      write(*,*) 'Calculating Plotting Data'
C
      PTX=.5+(6.-PLEN*ASPRAT*CHARHT)/2.
      PTY=4.5
      PTX1=.5+(6.-PLEN1*ASPRAT*CHARH1)/2.
      PTY1=4.1
      NCHAR=ifix(PLEN)
      NCHAR1=ifix(PLEN1)
C
      call PLOTS(0,IOPORT,MODEL)
      call FACTOR(1.00)
      call ASPECT(ASPRAT)
C ... Draw a Border ...
      if ((DISOPT .eq. 'P') .or. (DISOPT .eq. 'p')) then
         call PLOT(XORG,YORG,-13)
         call PLOT(8.0,0.0,2)
         call PLOT(8.0,6.0,2)
         call PLOT(0.0,6.0,2)
         call PLOT(0.0,0.0,2)
      endif
C
C
C  ... This scaling applies when the X axis represents Time...
      X(NPTS+1)=BEGTIM
      FIRSTX = X(NPTS+1)
      X(NPTS+2)=(X(NPTS)-X(NPTS+1))/6.
      DELTAX = X(NPTS+2)
C
      call SCALE(Y,4.,NPTS,1)
      call SCALE(Z,4.,NPTS,1)
      if (Z(NPTS+2) .gt. Y(NPTS+2)) then
         Y(NPTS+2)=Z(NPTS+2)
      else
         Z(NPTS+2)=Y(NPTS+2)
      endif
      FIRSTY=Y(NPTS+1)
      DELTAY = Y(NPTS+2)
C
      call PLOT(1.25,1.,-13)
      call STAXIS(.15,.22,.12,.080,3)
      call AXIS(0.0,0.0,XTITLE,XLEN,6.,0.,FIRSTX,DELTAX)
      call STAXIS(.15,.22,.12,.080,2)
      call AXIS(0.0,0.0,YTITLE,YLEN,4.,90.,FIRSTY,DELTAY)
      call SYMBOL(PTX,PTY,CHARHT,PTITLE,0.,NCHAR)
      call SYMBOL(PTX1,PTY1,CHARH1,PTIT1,0.,NCHAR1)
      call LINE(X,Y,NPTS,1,0,0)
      call CURVE(X,Z,NPTS,-.1)
      call PLOT(0.,0.,999)
C
```

```
      MODEL=99
      IOPORT=99
C
      return
      end
C
C    *******************************************
C    ***** PULSE WIDTH MODULATOR MODULE *****
C    *******************************************
C
      Subroutine PWMOD(TIME,NUMIT,TSTART,PERIOD,TOGGLE,POSERR,
     +    DBAND,VIF,VIB,DIR,VREF,THRESH,KPWM)
C
      IMPLICIT REAL*4 (A-Z)
      INTEGER*2 NUMIT,DIR
      LOGICAL*2 WAITNG,TOGGLE
C
C ... Reset the saw-tooth reference signal ...
        if (TIME .ge. TSTART+PERIOD) then
          TSTART=TSTART+PERIOD
          TOGGLE=.true.
        endif
C
        if (POSERR .gt. (0.+DBAND)) then
          DIR=1
          ERROR=abs(KPWM*(POSERR-DBAND))
        elseif (POSERR .lt. (0.-DBAND)) then
          DIR=-1
          ERROR=abs(KPWM*(POSERR+DBAND))
        else
          ERROR=0.
        endif
        call LIMIT(0.,1.,ERROR,ERROR)
        call RAMP(TIME,TSTART,NREF)
        VREF=NREF/PERIOD
        THRESH=1.-ERROR
C
C  ... "WAITNG" is a logical variable indicating whether or not a new
C       pulse may be generated ...
        if (NUMIT .eq. 1) WAITNG=TOGGLE
C
        if (WAITNG) then
          if (VREF .gt. THRESH) then
            if (DIR .eq. 1) then
              VIF=75.
              VIB=-75.
              TOGGLE=.false.
            elseif (DIR .eq. -1) then
              VIF=75.
              VIB=-75.
              TOGGLE=.false.
            endif
          elseif (VREF .lt. THRESH) then
            VIF=0.
            VIB=0.
            TOGGLE=.true.
          endif
        endif
C
      return
      end
C
C     *************************
C     ***** RELAY MODULE *****
C     *************************
C
      Subroutine RELAY(POSERR,DBAND,VIF,VIB,DIR)
C
      implicit REAL*4 (A-Z)
      integer*2 DIR
C
         if (POSERR .gt. DBAND) then
            VIF=75.
            VIB=-75.
            DIR=1
         elseif (POSERR .lt. -DBAND) then
            VIF=75.
            VIB=-75.
            DIR=-1
         elseif (abs(POSERR) .le. DBAND) then
            VIF=0.
            VIB=0.
         endif
C
      return
      end
C
C     **********************************************
C     ***** Commutation Advance Subroutine *****
C     **********************************************
        Subroutine COMADV(THETA,PI,THADV,THCON,THRST)
          implicit REAL*4 (A-Z)
          THDEG=THETA*(180.0/PI)
          THRST=AMOD(THDEG,360.0)
          if (THRST .LT. 0.0) THRST=THRST+360.
          THCON=THRST+THADV
C
        return
        end
C
C     **************************************************
C     ***** Hall Sensor Positioning Subroutine *****
```

```
C     **************************************************
        Subroutine HALL(THCON,SE1,SE2,SE3)
          implicit REAL*4 (A-Z)
          if (THCON .ge. 180.0) THCON=THCON-180.
          if ((THCON .ge. 0.0) .and. (THCON .lt. 30.0)) go to 10
          if ((THCON .ge. 30.0) .and. (THCON .lt. 60.0)) go to 11
          if ((THCON .ge. 60.0) .and. (THCON .lt. 90.0)) go to 12
          if ((THCON .ge. 90.0) .and. (THCON .lt. 120.0)) go to 13
          if ((THCON .ge. 120.0) .and. (THCON .lt. 150.0)) go to 14
          if ((THCON .ge. 150.0) .and. (THCON .lt. 180.0)) go to 15
   10       SE1=1.
            SE2=0.
            SE3=1.
            go to 20
   11       SE1=1.
            SE2=0.
            SE3=0.
            go to 20
   12       SE1=1.
            SE2=1.
            SE3=0.
            go to 20
   13       SE1=0.
            SE2=1.
            SE3=0.
            go to 20
   14       SE1=0.
            SE2=1.
            SE3=1.
            go to 20
   15       SE1=0.
            SE2=0.
            SE3=1.
   20       continue
C
        return
        end
C     ********************************************
C     ***** General Commutation Subroutine *****
C     ********************************************
        Subroutine TRANSW(TIME,REVTIM,BEMFA,BEMFB,BEMFC,BEMFT,VEMFA,
     +            VEMFB,VEMFC,VIB,VIF,IM,IMA,IMB,IMC,VN1,VN2,SW1,
     +            SW2,SW3,SW4,SW5,SW6,THCON,THCON1,RSAT,POSIT,DIR,
     +            VD1D,VD2D,VD3D,VD4D,VD5D,VD6D,RIN,ROUT,RS,
     +            REQA1,REQA2,REQB1,REQB2,REQC1,REQC2,IAB,IBC,
     +            ICA,PVAO,PVBO,PVCO,NODE,TRIG1,TRIG2,TRIG3,
     +            TRIG4,TRIG5,TRIG6,RA,PLUG,VAIND,VBIND,VCIND)
        implicit REAL*4 (A-Z)
        integer*2 POSIT,DIR,TRIG1,TRIG2,TRIG3,TRIG4,TRIG5,TRIG6,PLUG
C
        THCON1=amod(THCON,180.0)
        if (THCON1 .lt. 0.0) THCON1=THCON1+180.
C
        IM=(abs(IMA)+abs(IMB)+abs(IMC))/2.
C
        if (TRIG1 .eq. 1) then
          PVAOX=abs(VAIND)+IMA*(RA+RIN/2.)
        elseif (TRIG2 .eq. 1) then
          PVAOX=-abs(VAIND)+IMA*(RA+RIN/2.)
        else
          PVAOX=VAIND+IMA*(RA+RIN/2.)
        endif
C
        if (TRIG3 .eq. 1) then
          PVBOX=abs(VBIND)+IMB*(RA+RIN/2.)
        elseif (TRIG4 .eq. 1) then
          PVBOX=-abs(VBIND)+IMB*(RA+RIN/2.)
        else
          PVBOX=VBIND+IMB*(RA+RIN/2.)
        endif
C
        if (TRIG5 .eq. 1) then
          PVCOX=abs(VCIND)+IMC*(RA+RIN/2.)
        elseif (TRIG6 .eq. 1) then
          PVCOX=-abs(VCIND)+IMC*(RA+RIN/2.)
        else
          PVCOX=VCIND+IMC*(RA+RIN/2.)
        endif
C
        if ((DIR .eq. 1) .and. (PLUG .eq. 0)) then
          if ((THCON1 .ge. 0.0) .and. (THCON1 .lt. 30.0)) POSIT=1
          if ((THCON1 .ge. 30.0) .and. (THCON1 .lt. 60.0)) POSIT=2
          if ((THCON1 .ge. 60.0) .and. (THCON1 .lt. 90.0)) POSIT=3
          if ((THCON1 .ge. 90.0) .and. (THCON1 .lt. 120.0)) POSIT=4
          if ((THCON1 .ge. 120.0) .and. (THCON1 .lt. 150.0)) POSIT=5
          if ((THCON1 .ge. 150.0) .and. (THCON1 .lt. 180.0)) POSIT=6
        elseif ((DIR .eq. -1) .and. (PLUG .eq. 0)) then
          if ((THCON1 .ge. 0.0) .and. (THCON1 .lt. 30.0)) POSIT=4
          if ((THCON1 .ge. 30.0) .and. (THCON1 .lt. 60.0)) POSIT=5
          if ((THCON1 .ge. 60.0) .and. (THCON1 .lt. 90.0)) POSIT=6
          if ((THCON1 .ge. 90.0) .and. (THCON1 .lt. 120.0)) POSIT=1
          if ((THCON1 .ge. 120.0) .and. (THCON1 .lt. 150.0)) POSIT=2
          if ((THCON1 .ge. 150.0) .and. (THCON1 .lt. 180.0)) POSIT=3
        endif
          if (POSIT .eq. 1) then
C
C    ( NODE is the WYE center point floating voltage )
            NODE=-(PVCOX+PVBOX)+float(DIR)*(VEMFC-VEMFB)
            if (PLUG .eq. 0) then
              SW1=0.
              SW2=0.
              SW3=0.
          SW4=1.
          SW5=1.
          SW6=0.
C
          IAB=0.
          ICA=0.
          BEMFT=BEMFC-BEMFB
          VN1=VIF-VEMFC
          VN2=VIB-VEMFB
C
          VD1D=(VIF-IM*(RS+ROUT)/2.)-(PVAOX+VEMFA+NODE)
          if (VD1D .le. -.6) TRIG1 = 1
C
          VD2D=(PVAOX+VEMFA+NODE)-(VIB+IM*(RS+ROUT)/2.)
          if (VD2D .le. -.6) TRIG2 = 1
C
          VD3D=(VIF-IM*(RS+ROUT)/2.)-(PVBOX+VEMFB+NODE)
          if (VD3D .le. -.6) TRIG3 = 1
C
          VD4D=-IMB*REQB2
          if (VD4D .le. -.6) TRIG4 = 1
C
          VD5D=IMC*REQC1
          if (VD5D .le. -.6) TRIG5 = 1
C
          VD6D=(PVCOX+VEMFC+NODE)-(VIB+IM*(RS+ROUT)/2.)
          if (VD6D .le. -.6) TRIG6 = 1
C
        elseif (PLUG .eq. 1) then
          SW1=0.
          SW2=0.
          SW3=0.
          SW4=1.
          SW5=0.
          SW6=0.
C
          IAB=0.
          IBC=0.
          ICA=0.
          BEMFT=BEMFC-BEMFB
          VN1=VIF-VEMFC
          VN2=VIB-VEMFB
C
          VD1D=(VIF-IM*(RS+ROUT)/2.)-(PVAOX+VEMFA+NODE)
          if (VD1D .le. -.6) TRIG1 = 1
C
          VD2D=(PVAOX+VEMFA+NODE)-(VIB+IM*(RS+ROUT)/2.)
          if (VD2D .le. -.6) TRIG2 = 1
C
          VD3D=(VIF-IM*(RS+ROUT)/2.)-(PVBOX+VEMFB+NODE)
          if (VD3D .le. -.6) TRIG3 = 1
```

```
C
            VD4D=(PVBOX+VEMFB+NODE)-(VIB+IM*(RS+ROUT)/2.)
            if (VD4D .le. -.6) TRIG4 = 1
C
            VD5D=(VIF-IM*(RS+ROUT)/2.)-(PVCOX+VEMFC+NODE)
            if (VD5D .le. -.6) TRIG5 = 1
C
            VD6D=(PVCOX+VEMFC+NODE)-(VIB+IM*(RS+ROUT)/2.)
            if (VD6D .le. -.6) TRIG6 = 1
C
          endif
C
        elseif (POSIT .eq. 2) then
C
          NODE=-(PVAOX+PVBOX)+float(DIR)*(VEMFB-VEMFA)
          if (PLUG .eq. 0) then
            SW1=1.
            SW2=0.
            SW3=0.
            SW4=1.
            SW5=0.
            SW6=0.
C
            IBC=0.
            ICA=0.
            BEMFT=BEMFA-BEMFB
            VN1=VIF-VEMFA
            VN2=VIB-VEMFB
C
            VD1D=IMA*REQA1
            if (VD1D .le. -.6) TRIG1 = 1
C
            VD2D=(PVAOX+VEMFA+NODE)-(VIB+IM*(RS+ROUT)/2.)
            if (VD2D .le. -.6) TRIG2 = 1
C
            VD3D=(VIF-IM*(RS+ROUT)/2.)-(PVBOX+VEMFB+NODE)
            if (VD3D .le. -.6) TRIG3 = 1
C
            VD4D=-IMB*REQB2
            if (VD4D .le. -.6) TRIG4 = 1
C
            VD5D=(VIF-IM*(RS+ROUT)/2.)-(PVCOX+VEMFC+NODE)
            if (VD5D .le. -.6) TRIG5 = 1
C
            VD6D=(PVCOX+VEMFC+NODE)-(VIB+IM*(RS+ROUT)/2.)
            if (VD6D .le. -.6) TRIG6 = 1
C
          elseif (PLUG .eq. 1) then
            SW1=0.
            SW2=0.
            SW3=0.
```

```
              SW4=1.
              SW5=0.
              SW6=0.
C
              IAB=0.
              IBC=0.
              ICA=0.
              BEMFT=BEMFA-BEMFB
              VN1=VIF-VEMFA
              VN2=VIB-VEMFB
C
              VD1D=(VIF-IM*(RS+ROUT)/2.)-(PVAOX+VEMFA+NODE)
              if (VD1D .le. -.6) TRIG1 = 1
C
              VD2D=(PVAOX+VEMFA+NODE)-(VIB+IM*(RS+ROUT)/2.)
              if (VD2D .le. -.6) TRIG2 = 1
C
              VD3D=(VIF-IM*(RS+ROUT)/2.)-(PVBOX+VEMFB+NODE)
              if (VD3D .le. -.6) TRIG3 = 1
C
              VD4D=(PVBOX+VEMFB+NODE)-(VIB+IM*(RS+ROUT)/2.)
              if (VD4D .le. -.6) TRIG4 = 1
C
              VD5D=(VIF-IM*(RS+ROUT)/2.)-(PVCOX+VEMFC+NODE)
              if (VD5D .le. -.6) TRIG5 = 1
C
              VD6D=(PVCOX+VEMFC+NODE)-(VIB+IM*(RS+ROUT)/2.)
              if (VD6D .le. -.6) TRIG6 = 1
C
            endif
C
           elseif (POSIT .eq. 3) then
C
            NODE=-(PVAOX+PVCOX)+float(DIR)*(VEMFA-VEMFC)
            if (PLUG .eq. 0) then
              SW1=1.
              SW2=0.
              SW3=0.
              SW4=0.
              SW5=0.
              SW6=1.
              IAB=0.
              IBC=0.
              BEMFT=BEMFA-BEMFC
              VN1=VIF-VEMFA
              VN2=VIB-VEMFC
C
              VD1D=IMA*REQA1
              if (VD1D .le. -.6) TRIG1 = 1
C
              VD2D=(PVAOX+VEMFA+NODE)-(VIB+IM*(RS+ROUT)/2.)
```

```
          if (VD2D .le. -.6) TRIG2 = 1
c
          VD3D=(VIF-IM*(RS+ROUT)/2.)-(PVBOX+VEMFB+NODE)
          if (VD3D .le. -.6) TRIG3 = 1
c
          VD4D=(PVBOX+VEMFB+NODE)-(VIB+IM*(RS+ROUT)/2.)
          if (VD4D .le. -.6) TRIG4 = 1
c
          VD5D=(VIF-IM*(RS+ROUT)/2.)-(PVCOX+VEMFC+NODE)
          if (VD5D .le. -.6) TRIG5 = 1
c
          VD6D=-IMC*REQC2
          if (VD6D .le. -.6) TRIG6 = 1
c
        elseif (PLUG .eq. 1) then
          SW1=0.
          SW2=0.
          SW3=0.
          SW4=0.
          SW5=0.
          SW6=1.
          IAB=0.
          IBC=0.
          ICA=0.
          BEMFT=BEMFA-BEMFC
          VN1=VIF-VEMFA
          VN2=VIB-VEMFC
c
          VD1D=(VIF-IM*(RS+ROUT)/2.)-(PVAOX+VEMFA+NODE)
          if (VD1D .le. -.6) TRIG1 = 1
c
          VD2D=(PVAOX+VEMFA+NODE)-(VIB+IM*(RS+ROUT)/2.)
          if (VD2D .le. -.6) TRIG2 = 1
c
          VD3D=(VIF-IM*(RS+ROUT)/2.)-(PVBOX+VEMFB+NODE)
          if (VD3D .le. -.6) TRIG3 = 1
c
          VD4D=(PVBOX+VEMFB+NODE)-(VIB+IM*(RS+ROUT)/2.)
          if (VD4D .le. -.6) TRIG4 = 1
c
          VD5D=(VIF-IM*(RS+ROUT)/2.)-(PVCOX+VEMFC+NODE)
          if (VD5D .le. -.6) TRIG5 = 1
c
          VD6D=(PVCOX+VEMFC+NODE)-(VIB+IM*(RS+ROUT)/2.)
          if (VD6D .le. -.6) TRIG6 = 1
c
        endif
c
       elseif (POSIT .eq. 4) then
c
        NODE=-(PVBOX+PVCOX)+float(DIR)*(VEMFC-VEMFB)
```

```
          if (PLUG .eq. 0) then
            SW1=0.
            SW2=0.
            SW3=1.
            SW4=0.
            SW5=0.
            SW6=1.
C
            IAB=0.
            ICA=0.
            BEMFT=BEMFB-BEMFC
            VN1=VIF-VEMFB
            VN2=VIB-VEMFC
C
            VD1D=(VIF-IM*(RS+ROUT)/2.)-(PVAOX+VEMFA+NODE)
            if (VD1D .le. -.6) TRIG1 = 1
C
            VD2D=(PVAOX+VEMFA+NODE)-(VIB+IM*(RS+ROUT)/2.)
            if (VD2D .le. -.6) TRIG2 = 1
C
            VD3D=IMB*REQB1
            if (VD3D .le. -.6) TRIG3 = 1
C
            VD4D=(PVBOX+VEMFB+NODE)-(VIB+IM*(RS+ROUT)/2.)
            if (VD4D .le. -.6) TRIG4 = 1
C
            VD5D=(VIF-IM*(RS+ROUT)/2.)-(PVCOX+VEMFC+NODE)
            if (VD5D .le. -.6) TRIG5 = 1
C
            VD6D=-IMC*REQC2
            if (VD6D .le. -.6) TRIG6 = 1
C
          elseif (PLUG .eq. 1) then
            SW1=0.
            SW2=0.
            SW3=0.
            SW4=0.
            SW5=0.
            SW6=1.
C
            IAB=0.
            IBC=0.
            ICA=0.
            BEMFT=BEMFB-BEMFC
            VN1=VIF-VEMFB
            VN2=VIB-VEMFC
C
            VD1D=(VIF-IM*(RS+ROUT)/2.)-(PVAOX+VEMFA+NODE)
            if (VD1D .le. -.6) TRIG1 = 1
C
            VD2D=(PVAOX+VEMFA+NODE)-(VIB+IM*(RS+ROUT)/2.)
            if (VD2D .le. -.6) TRIG2 = 1
c
            VD3D=(VIF-IM*(RS+ROUT)/2.)-(PVBOX+VEMFB+NODE)
            if (VD3D .le. -.6) TRIG3 = 1
c
            VD4D=(PVBOX+VEMFB+NODE)-(VIB+IM*(RS+ROUT)/2.)
            if (VD4D .le. -.6) TRIG4 = 1
c
            VD5D=(VIF-IM*(RS+ROUT)/2.)-(PVCOX+VEMFC+NODE)
            if (VD5D .le. -.6) TRIG5 = 1
c
            VD6D=(PVCOX+VEMFC+NODE)-(VIB+IM*(RS+ROUT)/2.)
            if (VD6D .le. -.6) TRIG6 = 1
c
          endif
c
         elseif (POSIT .eq. 5) then
c
          NODE=-(PVBOX+PVAOX)+float(DIR)*(VEMFB-VEMFA)
          if (PLUG .eq. 0) then
            SW1=0.
            SW2=1.
            SW3=1.
            SW4=0.
            SW5=0.
            SW6=0.
c
            IBC=0.
            ICA=0.
            BEMFT=BEMFB-BEMFA
            VN1=VIF-VEMFB
            VN2=VIB-VEMFA
c
            VD1D=(VIF-IM*(RS+ROUT)/2.)-(PVAOX+VEMFA+NODE)
            if (VD1D .le. -.6) TRIG1 = 1
c
            VD2D=-IMA*REQA2
            if (VD2D .le. -.6) TRIG2 = 1
c
            VD3D=IMB*REQB1
            if (VD3D .le. -.6) TRIG3 = 1
c
            VD4D=(PVBOX+VEMFB+NODE)-(VIB+IM*(RS+ROUT)/2.)
            if (VD4D .le. -.6) TRIG4 = 1
c
            VD5D=(VIF-IM*(RS+ROUT)/2.)-(PVCOX+VEMFC+NODE)
            if (VD5D .le. -.6) TRIG5 = 1
c
            VD6D=(PVCOX+VEMFC+NODE)-(VIB+IM*(RS+ROUT)/2.)
            if (VD6D .le. -.6) TRIG6 = 1
c
```

```
           elseif (PLUG .eq. 1) then
             SW1=0.
             SW2=1.
             SW3=0.
             SW4=0.
             SW5=0.
             SW6=0.
C
             IAB=0.
             IBC=0.
             ICA=0.
             BEMFT=BEMFB-BEMFA
             VN1=VIF-VEMFB
             VN2=VIB-VEMFA
C
             VD1D=(VIF-IM*(RS+ROUT)/2.)-(PVAOX+VEMFA+NODE)
             if (VD1D .le. -.6) TRIG1 = 1
C
             VD2D=(PVAOX+VEMFA+NODE)-(VIB+IM*(RS+ROUT)/2.)
             if (VD2D .le. -.6) TRIG2 = 1
C
             VD3D=(VIF-IM*(RS+ROUT)/2.)-(PVBOX+VEMFB+NODE)
             if (VD3D .le. -.6) TRIG3 = 1
C
             VD4D=(PVBOX+VEMFB+NODE)-(VIB+IM*(RS+ROUT)/2.)
             if (VD4D .le. -.6) TRIG4 = 1
C
             VD5D=(VIF-IM*(RS+ROUT)/2.)-(PVCOX+VEMFC+NODE)
             if (VD5D .le. -.6) TRIG5 = 1
C
             VD6D=(PVCOX+VEMFC+NODE)-(VIB+IM*(RS+ROUT)/2.)
             if (VD6D .le. -.6) TRIG6 = 1
C
           endif
C
          elseif (POSIT .eq. 6) then
C
           NODE=-(PVCOX+PVAOX)+float(DIR)*(VEMFA-VEMFC)
           if (PLUG .eq. 0) then
             SW1=0.
             SW2=1.
             SW3=0.
             SW4=0.
             SW5=1.
             SW6=0.
C
             IAB=0.
             IBC=0.
             BEMFT=BEMFC-BEMFA
             VN1=VIF-VEMFC
             VN2=VIB-VEMFA
```

```
c
          VD1D=(VIF-IM*(RS+ROUT)/2.)-(PVAOX+VEMFA+NODE)
          if (VD1D .le. -.6) TRIG1 = 1
c
          VD2D=-IMA*REQA2
          if (VD2D .le. -.6) TRIG2 = 1
c
          VD3D=(VIF-IM*(RS+ROUT)/2.)-(PVBOX+VEMFB+NODE)
          if (VD3D .le. -.6) TRIG3 = 1
c
          VD4D=(PVBOX+VEMFB+NODE)-(VIB+IM*(RS+ROUT)/2.)
          if (VD4D .le. -.6) TRIG4 = 1
c
          VD5D=IMC*REQC1
          if (VD5D .le. -.6) TRIG5 = 1
c
          VD6D=(PVCOX+VEMFC+NODE)-(VIB+IM*(RS+ROUT)/2.)
          if (VD6D .le. -.6) TRIG6 = 1
c
        elseif (PLUG .eq. 1) then
          SW1=0.
          SW2=1.
          SW3=0.
          SW4=0.
          SW5=0.
          SW6=0.
c
          IAB=0.
          IBC=0.
          ICA=0.
          BEMFT=BEMFC-BEMFA
          VN1=VIF-VEMFC
          VN2=VIB-VEMFA
c
          VD1D=(VIF-IM*(RS+ROUT)/2.)-(PVAOX+VEMFA+NODE)
          if (VD1D .le. -.6) TRIG1 = 1
c
          VD2D=(PVBOX+VEMFB+NODE)-(VIB+IM*(RS+ROUT)/2.)
          if (VD2D .le. -.6) TRIG2 = 1
c
          VD3D=(VIF-IM*(RS+ROUT)/2.)-(PVBOX+VEMFB+NODE)
          if (VD3D .le. -.6) TRIG3 = 1
c
          VD4D=(PVBOX+VEMFB+NODE)-(VIB+IM*(RS+ROUT)/2.)
          if (VD4D .le. -.6) TRIG4 = 1
c
          VD5D=(VIF-IM*(RS+ROUT)/2.)-(PVCOX+VEMFC+NODE)
          if (VD5D .le. -.6) TRIG5 = 1
c
          VD6D=(PVCOX+VEMFC+NODE)-(VIB+IM*(RS+ROUT)/2.)
          if (VD6D .le. -.6) TRIG6 = 1
```

```
C
             endif
C
            endif
   99     continue
          return
          end
C     ****************************************************
C     ***** Cutoff-Saturation Limiting Subroutine *****
C     ****************************************************
            Subroutine LIMIT(RSAT,RCUT,INPUT,OUT)
              implicit REAL*4 (A-Z)
              if (INPUT .le. RSAT) then
                OUT=RSAT
              elseif (INPUT .ge. RCUT) then
                OUT=RCUT
              else
                OUT=INPUT
              end if
C
            return
            end
C     ****************************************
C     ***** Function Switch Subroutine *****
C     ****************************************
          Subroutine FCNSW(X1,X2,X3,X4,OUT)
            implicit REAL*4 (A-Z)
            if (X1 .lt. 0.0) then
              OUT=X2
            elseif (X1 .eq. 0.0) then
              OUT=X3
            else
              OUT=X4
            end if
C
          return
          end
C     **************************************
C     ***** Step function Subroutine *****
C     **************************************
          Subroutine STEP(TIME,TSTEP,OUT)
            implicit REAL*4 (A-Z)
            if (TIME .ge. TSTEP) then
              OUT=1.0
            else
              OUT=0.0
            end if
C
          return
          end
C     ***********************************
```

```
C     ***** Deadspace Subroutine *****
C     ********************************
         Subroutine DEADSP(P1,P2,VSGDEL,VSGERR)
           implicit REAL*4 (A-Z)
           if (VSGDEL .gt. P2) then
             VSGERR=VSGDEL-P2
           elseif (VSGDEL .lt. P1) then
             VSGERR=VSGDEL-P1
           else
             VSGERR=0.0
           end if
C
         return
         end
C     ***************************
C     ***** Ramp Subroutine *****
C     ***************************
         Subroutine RAMP(TIME,TRAMP,OUT)
           implicit REAL*4 (A-Z)
           if (TIME .ge. TRAMP) then
             OUT=TIME-TRAMP
           else
             OUT=0.0
           end if
C
         return
         end
C      *******************
C      *** TIME CONSTANT ***
C      *******************
C
       Subroutine TCONST(Y0,X,TAU,NTIME,NTIM,DELTIM,Y)
         implicit real*4 (A-Z)
         integer*2 NTIME,NTIM
         if (NTIME .eq. 1) Y=Y0
         if (NTIME .ne. NTIM) Y0=Y
         DECAY=exp(-DELTIM/TAU)
         Y=Y0+(X-Y0)*(1.-DECAY)
         if (NTIME .eq. 1) Y=Y0
         NTIM=NTIME
C
       return
       end
C     *********************************************
C     ***** First Order Derivative Subroutine *****
C     *****    (Central Difference Method)    *****
C     *********************************************
         Subroutine DERIV(DELTIM,NTIME,NTIM1,IC2,XM1,NOWVAL,XX,XDM1,
     +                    XD,XDDM1,XDD,SLOPE)
           implicit REAL*4 (A-Z)
           integer*2 NTIME,NTIM1
```

```
C
          if (NTIME .eq. NTIM1) then
            XX=NOWVAL
          else
            XM1=XX
            XX=NOWVAL
            XDM1=XD
            XDDM1=XDD
          end if
C
          XD=(XX-XM1)/DELTIM
          if (abs(XD) .lt. 1.E-8) XD=0.
          if (NTIME .eq. 1) XD=IC2
          XDD=(XD-XDM1)/DELTIM
          if (abs(XDD) .lt. 1.E-8) XDD=0.0
C
          NTIM1=NTIME
C
          XPRED=XX+XD*DELTIM+XDD*(DELTIM**2)/2.0
          if (abs(XPRED) .lt. 1.E-8) XPRED=0.0
          SLOPE=(XPRED-XM1)/(2.0*DELTIM)
          if (abs(SLOPE) .lt. 1.E-8) SLOPE=0.0
C
        return
        end
C    ***********************************************
C    ***** Trapezoidal Integration Subroutine *****
C    ***********************************************
        Subroutine INTGRL(NTIME,NTIM2,DELTIM,IC3,PREVAL,NOWVAL,
     +                    CURVAL,OUTOLD,OUTNEW)
          implicit REAL*4 (A-Z)
          integer*2 NTIME,NTIM2
C
          if ((NTIME .eq. NTIM2) .or. (NTIME .eq. 1)) then
            CURVAL=NOWVAL
          else
            PREVAL = CURVAL
            CURVAL = NOWVAL
            OUTOLD = OUTNEW
          end if
          if (NTIME .eq. 1) OUTOLD=IC3
          OUTNEW  = OUTOLD+(CURVAL+PREVAL)*DELTIM/2.
          NTIM2=NTIME
C
        return
        end
C    ****************************************
C    ***** CLEAR SCREEN AND HOME CURSOR *****
C    ****************************************
      subroutine CLRSCR
      character*1 C1,C2,C3,C4
      integer*2 IC(4)
      equivalence (C1,IC(1)),(C2,IC(2)),(C3,IC(3)),(C4,IC(4))
      data IC/16#1B,16#5B,16#32,16#4A/
C
C *** Write Escape Code to Display ***
      write(*,1) C1,C2,C3,C4
    1 format(1X,4A1)
C
      return
      end
C    ******************************************
C    ***** Position Cursor by Row,Column *****
C    ******************************************
      subroutine GOTOXY(ROW,COLUMN)
      integer*2 IC(4),ROW,COLUMN,L
      character*1 C1,C2,C5,C8,LC(5)
      character*5 CBUFF
      equivalence (C1,IC(1)),(C2,IC(2)),(C5,IC(3)),(C8,IC(4)),
     +            (CBUFF,LC(1))
      data IC/16#1B,16#5B,16#3B,16#66/
C
      L=10000+100*ROW+COLUMN
C
C *** Write Escape Codes to a Character Buffer ***
      write(CBUFF,2) L
    2 format(I5)
C
C *** Write Escape Codes to Display ***
      write(*,3) C1,C2,LC(2),LC(3),C5,LC(4),LC(5),C8
    3 format(1X,8A1,\)
      return
      end
```

APPENDIX B

PWM OPEN LOOP TRANSFER CHARACTERISTICS

```
$NOfloatcalls
$NOdebug
C
C     ________________________________________________
C    |                                                |
C    |  ROSSITTO, VS   THESIS    PROF GERBA  04/11/87 |
C    |____________PWM TEST MODULE_____________________|
C
C     This version tests the pulse width modulator for logical
C     correctness. POSERR is used as an input and VIN is the
C     output.
      IMPLICIT REAL*4 (A-Z)
      COMMON BEGTIM,FINTIM,NPTS,IOPORT,MODEL,XLEN,YLEN,PLEN,PPLANE,
     +       XTITLE,YTITLE,PTITLE
      REAL*4 X(1010),Y1(1010),Y2(1010),Y3(1010),Y4(1010),LINE0(1010)
      INTEGER*2 NTERMS,IOPORT,MODEL,XLEN,YLEN,NTIME,NUMIT,NTIM1,
     +          NTIM2,NTIM3,NTIM4,DIR,PMODEL,NPTS,NCTR,PPLANE,
     +          SIM2PL,WAVE
      LOGICAL*2 WAITNG,TOGGLE
      CHARACTER*1 DISOPT,PLOPT
      CHARACTER*6 ANS1,ANS11,ANS21,PRTSEL
      CHARACTER*20 XTITLE,YTITLE
      CHARACTER*51 PRTCHR,PTITLE
C
C  ... Introductory Page (1 time good deal!)
      call CLRSCR
      write(*,4)
      PAUSE
C     *******************************************
C     *** OPEN/READ/CLOSE INPUT DATA FILE ***
C     *******************************************
C
 13   open(7,FILE='PWM.INP',STATUS='OLD',ACCESS='SEQUENTIAL')
      read(7,1000) PMODEL,PRTCHR
      read(7,1020) BEGTIM,FINTIM,MAXITS,SIM2PL
      read(7,1022) DBAND,PERIOD
      read(7,1028) KPWM,X0,Y0,WFACT
      close(7,STATUS='KEEP')
C
C     ***************************************
C     *** DISPLAY MAIN MENU SELECTIONS ***
C     ***************************************
C
    1 call CLRSCR
      call GOTOXY(10,1)
      write(*,5)
      read(*,'(A)') ANS1
C  ... Hardware Options ...
      if ((ANS1 .eq. 'h') .or. (ANS1 .eq. 'H')) then
C
 101     call CLRSCR
         call GOTOXY(17,24)
         write(*,*)'*** CURRENT PRINTER SELECTION ***'
         call GOTOXY(20,20)
         write(*,*) PRTCHR
         call GOTOXY(10,1)
         write(*,105)
         read(*,'(A)') ANS11
C
C  ... Printer Options ...
         if ((ANS11 .eq. 'p') .or. (ANS11 .eq. 'P')) then
 131        call CLRSCR
            write(*,130)
            read(*,'(A)') PRTSEL
C
            if (PRTSEL .eq. '0') then
               PRTCHR='Epson FX-80 Printer, single density'
               PMODEL=0
            elseif (PRTSEL .eq. '1') then
               PRTCHR='Epson FX-80 Printer, double density'
               PMODEL=1
            elseif (PRTSEL .eq. '2') then
               PRTCHR='Epson FX-80 Printer, dble spd,dual density'
               PMODEL=2
            elseif (PRTSEL .eq. '3') then
               PRTCHR='Epson FX-80 Printer, quad density'
               PMODEL=3
            elseif (PRTSEL .eq. '4') then
               PRTCHR='Epson FX-80 Printer, CRT Graphics I'
               PMODEL=4
            elseif (PRTSEL .eq. '5') then
               PRTCHR='Epson FX-80 Printer, plotter graphics'
               PMODEL=5
            elseif (PRTSEL .eq. '6') then
               PRTCHR='Epson FX-80 Printer, CRT Graphics II'
               PMODEL=6
            elseif (PRTSEL .eq. '10') then
               PRTCHR='Epson FX-100 Printer, single density'
               PMODEL=7
            elseif (PRTSEL .eq. '11') then
               PRTCHR='Epson FX-100 Printer, double density'
               PMODEL=11
            elseif (PRTSEL .eq. '12') then
               PRTCHR='Epson FX-100 Printer, dble spd,dual density'
               PMODEL=12
            elseif (PRTSEL .eq. '13') then
               PRTCHR='Epson FX-100 Printer, quad density'
```

```
                PMODEL=13
             elseif (PRTSEL .eq. '14') then
                PRTCHR='Epson FX-100 Printer, CRT Graphics I'
                PMODEL=14
             elseif (PRTSEL .eq. '15') then
                PRTCHR='Epson FX-100 Printer, plotter graphics'
                PMODEL=15
             elseif (PRTSEL .eq. '16') then
                PRTCHR='Epson FX-100 Printer, CRT Graphics II'
                PMODEL=16
             elseif (PRTSEL .eq. '20') then
                PRTCHR='HP 7470A Graphics Plotter'
                PMODEL=20
             elseif (PRTSEL .eq. '30') then
                PRTCHR='HP 7475A Graphics Plotter'
                PMODEL=30
             elseif (PRTSEL .eq. '60') then
                PRTCHR='HP 2686A Laser Jet Printer'
                PMODEL=60
C
C  ... Quit the Printer Menu ...
             elseif ((PRTSEL .eq. 'Q') .or. (PRTSEL .eq. 'q')) then
                go to 101
             else
                go to 131
             endif
             go to 101
C
C  ... Quit the Hardware Menu ...
          elseif((ANS11 .eq. 'q') .or. (ANS11 .eq. 'Q')) then
             go to 1
          else
             go to 101
          endif
C
C  ... PWM Design Menu ...
       elseif ((ANS1 .eq. 'p') .or. (ANS1 .eq. 'P')) then
C
 203      call CLRSCR
          write(*,250) KPWM,DBAND,PERIOD
          read(*,'(A)') ANS21
C
          if (ANS21 .eq. 'KPWM') then
             call GOTOXY(24,1)
             write(*,'(A\)')'Enter a REAL value for KPWM--> '
             read(*,*) KPWM
             go to 203
          elseif (ANS21 .eq. 'PERIOD') then
             call GOTOXY(24,1)
             write(*,'(A\)')'Enter a REAL value for PERIOD--> '
             read(*,*) PERIOD
```

```
               go to 203
            elseif (ANS21 .eq. 'DBAND') then
               call GOTOXY(24,1)
               write(*,'(A\)')'Enter a REAL value for DBAND--> '
               read(*,*) DBAND
               go to 203
C
C  ... Quit PWM Design Menu ...
            elseif (ANS21 .eq. 'Q') then
               go to 1
            else
               go to 203
            end if
C
C  ... Simulation Options ...
         elseif ((ANS1 .eq. 'o') .or. (ANS1 .eq. 'O')) then
C
 202        call CLRSCR
C
            DELTIM=(FINTIM-BEGTIM)/(1000.*SIM2PL)
            if (FINTIM/DELTIM .gt. MAXITS) DELTIM =FINTIM/MAXITS
            NTERMS=IFIX(FINTIM/DELTIM)+1
C
            write(*,240) BEGTIM,FINTIM,MAXITS,SIM2PL,
     +                   X0,Y0,WFACT,DELTIM,NTERMS
            read(*,'(A)') ANS21
C
            if (ANS21 .eq. 'BEGTIM') then
               call GOTOXY(24,1)
               write(*,'(A\)')'Enter a REAL value for BEGTIM--> '
               read(*,*) BEGTIM
               go to 202
            elseif (ANS21 .eq. 'FINTIM') then
               call GOTOXY(24,1)
               write(*,'(A\)')'Enter a REAL value for FINTIM--> '
               read(*,*) FINTIM
               go to 202
            elseif (ANS21 .eq. 'MAXITS') then
               call GOTOXY(24,1)
               write(*,'(A\)')'Enter a REAL value for MAXITS--> '
               read(*,*) MAXITS
               go to 202
            elseif (ANS21 .eq. 'SIM2PL') then
               call GOTOXY(24,1)
               write(*,'(A\)')'Enter a INTEGER value for SIM2PL--> '
               read(*,*) SIM2PL
               go to 202
            elseif (ANS21 .eq. 'X0') then
               call GOTOXY(24,1)
               write(*,'(A\)')'Enter a REAL value for X0--> '
               read(*,*) X0
```

```
             go to 202
          elseif (ANS21 .eq. 'Y0') then
             call GOTOXY(24,1)
             write(*,'(A\)')'Enter a REAL value for Y0--> '
             read(*,*) Y0
             go to 202
          elseif (ANS21 .eq. 'WFACT') then
             call GOTOXY(24,1)
             write(*,'(A\)')'Enter a REAL value for WFACT--> '
             read(*,*) WFACT
             go to 202
C  ... Quit Simulation Options Menu ...
          elseif (ANS21 .eq. 'Q') then
             go to 1
          else
             go to 202
          end if
C
C  ... Input Waveform Options ...
       elseif ((ANS1 .eq. 'i') .or. (ANS1 .eq. 'I')) then
C
 204      call CLRSCR
C
C
          write(*,260)
          read(*,'(A)') ANS21
          call CLRSCR
C
          if (ANS21 .eq. '1') then
             call GOTOXY(10,1)
             WAVE=1
             write(*,'(A\)')'Enter a REAL value for K--> '
             read(*,*) CONST
             write(*,'(A\)')' Enter a REAL value for W--> '
             read(*,*) W
             call GOTOXY(17,4)
             write(*,141) CONST,W
  141 format(1X,'POSERR =',F8.3,'* SIN(',F8.3,'* t)')
             PAUSE
             go to 204
          elseif (ANS21 .eq. '2') then
             call GOTOXY(10,1)
             WAVE=2
             write(*,'(A\)')'Enter a REAL value for K--> '
             read(*,*) CONST
             write(*,'(A\)')' Enter a REAL value for W--> '
             read(*,*) W
             write(*,'(A\)')' Enter a REAL value for TAU--> '
             read(*,*) TAU
             call GOTOXY(17,4)
             write(*,142) CONST,TAU,W
  142 format(1X,'POSERR =',F8.3,'* EXP(-t/',F8.4,')*SIN(',F8.3,'* t)')
            PAUSE
            go to 204
         elseif (ANS21 .eq. '3') then
            call GOTOXY(10,1)
            WAVE=3
            write(*,'(A\)')'Enter a REAL value for A--> '
            read(*,*) A
            write(*,'(A\)')' Enter a REAL value for B--> '
            read(*,*) B
            call GOTOXY(17,4)
            write(*,143) A,B
  143 format(1X,'POSERR =',F8.3,'* t +',F8.4)
            PAUSE
            go to 204
C  ... Quit Simulation Options Menu ...
         elseif (ANS21 .eq. 'Q') then
            go to 1
         else
            go to 204
         end if
C  ... Save Options to File ...
      elseif ((ANS1 .eq. 's') .or. (ANS1 .eq. 'S')) then
C
C     ******************************************
C     *** OPEN/WRITE/CLOSE INPUT DATA FILE ***
C     ******************************************
C
          open(7,FILE='PWM.INP',STATUS='NEW')
          write(7,1000) PMODEL,PRTCHR
          write(7,1020) BEGTIM,FINTIM,MAXITS,SIM2PL
          write(7,1022) DBAND,PERIOD
          write(7,1028) KPWM,X0,Y0,WFACT
          write(7,2000)
          close(7,STATUS='KEEP')
C
          go to 1
C
C  ... Run the Program ...
      elseif ((ANS1 .eq. 'r') .or. (ANS1 .eq. 'R')) then
          go to 2
C
C  ... Quit the Program ...
      elseif ((ANS1 .eq. 'q') .or. (ANS1 .eq. 'Q')) then
          stop
      else
          go to 1
      endif
C
  2   PI=3.14159
C
```

```
C  ... Initializations ...
      NCTR=0
      NPTS=0
      TSTART=0.0
      TOGGLE=.true.
      PPLANE=0
C
C ... Display the simulation header ...
      call CLRSCR
      call GOTOXY(10,29)
      write(*,*) 'Simulation in Progress'
      DELTIM=(FINTIM-BEGTIM)/(1000.*SIM2PL)
      if (FINTIM/DELTIM .gt. MAXITS) DELTIM =FINTIM/MAXITS
      NTERMS=IFIX(FINTIM/DELTIM)+1
      call GOTOXY(14,1)
      write(*,15) DELTIM,NTERMS
   15 format(16X,'Simulation Step Size --> ',F8.7,' seconds',/,
     +       17X,'Total Number of Steps--> ',I4)
      SPACE=DELTIM/2.0
C
C  ... Open/Write/Close OUTPUT data file ...
      open(4,FILE='PWM.OUT',STATUS='NEW')
      write(4,1200) BEGTIM,FINTIM,MAXITS,SIM2PL,PERIOD,DBAND,
     +              ERRCUT,AGCCUT,ERRSAT,AGCSAT
      close(4,STATUS='KEEP')
C
C     ************************************
C     *** START MAIN SIMULATION LOOP ***
C     ************************************
C
      DO 100 NTIME=1,NTERMS
        TIME=(NTIME-1)*DELTIM
C ... Reset the saw-tooth reference signal ...
        if (TIME .ge. TSTART+PERIOD) then
          TSTART=TSTART+PERIOD
          TOGGLE=.true.
        endif
C
        if (WAVE .eq. 1) POSERR=CONST*SIN(W*TIME)
        if (WAVE .eq. 2) POSERR=CONST*exp(-TIME/TAU)*SIN(W*TIME)
        if (WAVE .eq. 3) POSERR=A*TIME+B
C
        if (POSERR .gt. (0.+DBAND)) then
          DIR=1
          ERROR=abs(KPWM*(POSERR-DBAND))
        elseif (POSERR .lt. (0.-DBAND)) then
          DIR=-1
          ERROR=abs(KPWM*(POSERR+DBAND))
        else
          ERROR=0.
        endif
        call LIMIT(0.,1.,ERROR,ERROR)
        call RAMP(TIME,TSTART,NREF)
        VREF=NREF/PERIOD
        THRESH=1.-ERROR
C
C  ... "WAITING" is a logical variable indicating whether or not a new
C       pulse may be generated ...
        WAITNG=TOGGLE
C
        if (WAITNG) then
          if (VREF .gt. THRESH) then
            if (DIR .eq. 1) then
              VIN=150.
              TOGGLE=.false.
            elseif (DIR .eq. -1) then
              VIN=-150.
              TOGGLE=.false.
            endif
          else
            VIN=0.
            TOGGLE=.true.
          endif
        endif
C
      DIRLOG=VIN/150.
C
C  ... Generate Plotting Arrays ...
      if (TIME .ge. BEGTIM) then
        NCTR=NCTR+1
        if (mod(NCTR,SIM2PL) .eq. 0) then
          NPTS=NPTS+1
          X(NPTS)=TIME
          Y1(NPTS)=POSERR
          Y2(NPTS)=VREF
          Y3(NPTS)=THRESH
          Y4(NPTS)=DIRLOG
          LINE0(NPTS)=0.
        endif
      endif
C
  100 CONTINUE
C
C     **********************************
C     *** END MAIN SIMULATION LOOP ***
C     **********************************
C
C     ******************************
C     ***** Plotting selection *****
C     ******************************
C
C *** Clear Screen & Home Cursor ***
```

```
  400 call CLRSCR
C
      write(*,1305)
      read(*,'(A)') DISOPT
C
      if (DISOPT .eq. '1') then
        MODEL=99
        IOPORT=99
      elseif (DISOPT .eq. '2') then
        MODEL=PMODEL
        IOPORT=1
        if ((MODEL .eq. 20) .or. (MODEL .eq. 30)) IOPORT=9600
      elseif (DISOPT .eq. '3') then
        GO TO 13
      elseif ((DISOPT .eq. 'Q') .or. (DISOPT .eq. 'q')) then
        GO TO 460
      else
        write(*,*) 'Incorrect display option selection, try again !'
        go to 400
      end if
C
  410 call CLRSCR
      if (DISOPT .eq. '2') then
        call GOTOXY(20,20)
        write(*,*) PRTCHR
        call GOTOXY(1,1)
      endif
      write(*,1300)
      read(*,'(A)') PLOPT
C
      if ((PLOPT .eq. 'Q') .or. (PLOPT .eq. 'q')) then
        go to 400
      elseif (PLOPT .eq. '1') then
        XTITLE='TIME (sec)'
        XLEN=-10
        YTITLE='PWM PERFORMANCE'
        YLEN=14
        PPLANE=0
        call MGRAPH(X,Y1,Y2,Y3,Y4,LINE0,DISOPT,KPWM,DBAND,X0,Y0,WFACT)
      else
        go to 410
      endif
C
      go to 400
  460 continue
C
C     ******************************
C     *** I/O FORMAT STATEMENTS ***
C     ******************************
C
    4 format(////,24X,'PULSE WIDTH MODULATOR DESIGN AND ANALYSIS',/,
     +              26X,'.Open Loop Response Characteristics',/,
     +              26X,'.Automatic Gain Control Simulation',/,
     +              26X,'.INTEL-8087 Math Co-processor version',///,
     + 10X,'NOTE: Much of the screen control attained in this ',/,
     + 10X,'      program is interactive with the DOS screen driver',/,
     + 10X,'      ANSI.SYS.  Ensure your CONFIG.SYS file contains',/,
     + 10X,'      the statement "device=ANSI.SYS".',//,
     + 10X,'      The input data file PWM.INP must be in the ',/,
     + 10X,'      default disk drive. The output file PWM.OUT',/,
     + 10X,'      will be written to the default drive.',//)
C
    5 format(32X,'*** MAIN MENU ***',//,
     +        20X,'[H]----> HARDWARE Configuration Menu',/,
     +        20X,'[P]----> PWM Design Menu',/,
     +        20X,'[I]----> INPUT Waveform',/,
     +        20X,'[O]----> OPTIONS for Simulation',/,
     +        20X,'[S]----> SAVE All Changes',/,
     +        20X,'[R]----> RUN Simulation Program',/,
     +        20X,'[Q]----> QUIT the Program',//,
     +         8X,'ENTER SELECTION---->',\)
  105     format(30X,'*** HARDWARE MENU ***',//,
     +        20X,'[P]----> PRINTER/PLOTTER configuration change',/,
     +        20X,'[Q]----> QUIT THIS MENU',//,
     +         8X,'ENTER SELECTION---->',\)
 1000 format(1X,I3,2X,A50)
 1020 format(1x,3F12.7,1X,I3)
 1022 format(1X,2F12.7)
 1028 format(1X,,4F12.7)
 2000 format(1X,'END OF FILE')
C
  130 FORMAT(24X,'*** PRINTER OPTIONS MENU ***',//,
     +  15X,'[0] --> Epson FX-80 Printer, single density',/,
     +  15X,'[1] --> Epson FX-80 Printer, double density',/,
     +  15X,'[2] --> Epson FX-80 Printer, dble spd,dual density',/,
     +  15X,'[3] --> Epson FX-80 Printer, quad density',/,
     +  15X,'[4] --> Epson FX-80 Printer, CRT Graphics I',/,
     +  15X,'[5] --> Epson FX-80 Printer, plotter graphics',/,
     +  15X,'[6] --> Epson FX-80 Printer, CRT Graphics II',/,
     +  15X,'[10] -> Epson FX-100 Printer, single density',/,
     +  15X,'[11] -> Epson FX-100 Printer, double density',/,
     +  15X,'[12] -> Epson FX-100 Printer, dble spd,dual density',/,
     +  15X,'[13] -> Epson FX-100 Printer, quad density',/,
     +  15X,'[14] -> Epson FX-100 Printer, CRT Graphics I',/,
     +  15X,'[15] -> Epson FX-100 Printer, plotter graphics',/,
     +  15X,'[16] -> Epson FX-100 Printer, CRT Graphics II',/,
     +  15X,'[20] -> HP 7470A Graphics Plotter',/,
     +  15X,'[30] -> HP 7475A Graphics Plotter',/,
     +  15X,'[60] -> HP 2686A Laser Jet Printer (NPS installation)',/,
     +  15X,'[Q] -->    QUIT THIS MENU',//,
     +  3X,'Enter Printer Selection Integer or Q to QUIT ---> ',\)
C
```

```
 240  format(12X,'*** SIMULATION OPTIONS MENU ***',//,
    + 1X,F12.7,1X,'[BEGTIM]  Start Time of Plotting Window',/,
    + 1X,F12.7,1X,'[FINTIM]  Stop Time of Plotting Window',/,
    + 1X,F12.7,1X,'[MAXITS]  Max Number of Simulation Iterations',/,
    + 10X,I3,1X,'[SIM2PL]  Ratio: Points Simulated/Plotted',/,
    + 1X,F12.7,1X,'[X0]      X Coordinate for Plotting Origin',/,
    + 1X,F12.7,1X,'[Y0]      Y Coordinate for Plotting Origin',/,
    + 1X,F12.7,1X,'[WFACT]   Plotting Scaling Factor',/,
    + 14X,'[Q]       QUIT THIS MENU',///,
    + 15X,'Computed simulation step size ---> ',F8.7, 'seconds',/,
    + 15X,'Computed total number of steps---> ',I4,//,
    + 1X,'Enter variable name (UPPERCASE) or Q to QUIT ---> ',\)
C
 250  format(///,23X,'*** PWM DESIGN MENU ***',//,
    + 1X,F12.7,1X,'[KPWM]    PWM Amplifier Gain',/,
    + 1X,F12.7,1X,'[DBAND]   PWM Amplifier Deadband',/,
    + 1X,F12.7,1X,'[PERIOD]  Period of PWM Reference Cycle',/,
    + 14X,'[Q]       QUIT THIS MENU',//,
    + 1X,'Enter variable name (UPPERCASE) or Q to QUIT ---> ',\)
C
C
 260  format(///,13X,'*** INPUT WAVEFORM OPTIONS MENU ***',//,
    + 10X,'[1]       POSERR=K*sin(W*t)',/,
    + 10X,'[2]       POSERR=K*exp(-t/TAU)*sin(W*t)',/,
    + 10X,'[3]       POSERR=A*t+B',/,
    + 10X,'[Q]       QUIT THIS MENU',//,
    + 1X,'Enter [1,2,Q] ---> ',\)
C
 1200 format(20X,'PULSE WIDTH MODULATOR ANALYSIS',//,
    + 1X,F12.7,1X,'[BEGTIM]  Start Time of Plotting Window',/,
    + 1X,F12.7,1X,'[FINTIM]  Stop Time of Plotting Window',/,
    + 1X,F12.7,1X,'[MAXITS]  Max Number of Simulation Iterations',/,
    + 10X,I3,1X,'[SIM2PL]  Ratio: Points Simulated/Plotted',/,
    + 1X,F12.7,1X,'[PERIOD]  Period of PWM Reference Cycle',/,
    + 1X,F12.7,1X,'[DBAND]   Position Feedback Deadband',/,
    + 1X,F12.7,1X,'[KPWM]    PWM Amplifier Gain')
C
 1205 FORMAT(1X,F8.6,1X,1P5E12.3)
 1300 FORMAT(/////,2X,'The following are plotting options',//,
    +          5X,'[1] PWM Performance',/,
    +          5X,'[Q] QUIT THIS MENU',//,
    +          2X,'Enter selection [1,Q] ---> ',\)
C
 1305 FORMAT(/////,2X,'Display options:',/,
    +          5X,'[1] MONITOR',/,
    +          5X,'[2] PRINTER',/,
    +          5X,'[3] RETURN TO START-UP MENU (RE-INITIALIZE)',/,
    +          5X,'[Q] QUIT THE PROGRAM',//,
    +          2X,'Enter selection [1,2,3,Q] ---> ',\)
C
 1500 format(1X,I3,2X,A50)
```

```
C
      STOP
      END
C ------------------------------------------------------------------
C  **********************************
C  ***** PLOTTING SUBROUTINES *****
C  *****(single function plot)*****
C  **********************************
      Subroutine GRAPH(X,Y)
C
      implicit REAL*4 (A-Z)
      COMMON BEGTIM,FINTIM,NPTS,IOPORT,MODEL,XLEN,YLEN,PLEN,PPLANE,
     +       XTITLE,YTITLE,PTITLE
      real*4 X(1010),Y(1010)
      integer*2 NPTS,IOPORT,MODEL,XLEN,YLEN,PPLANE,NCHAR
      character*20 XTITLE,YTITLE
      character*51 PTITLE
C
      ASPRAT=.65
      CHARHT=.22
      PTX=1.5+(6.-PLEN*ASPRAT*CHARHT)/2.
      PTY=5.5
      NCHAR=ifix(PLEN)
C
      call PLOTS(0,IOPORT,MODEL)
      call FACTOR(1.00)
      call ASPECT(ASPRAT)
      call SCALE(X,6.,NPTS,1)
      call SCALE(Y,4.,NPTS,1)
      call STAXIS(.15,.22,.10,.080,3)
        FIRSTX = X(NPTS+1)
        if (PPLANE .eq. 1) then
          DELTAX=X(NPTS+2)
        else
          X(NPTS+2)=(X(NPTS)-X(NPTS+1))/6.
          DELTAX = X(NPTS+2)
        endif
        FIRSTY = Y(NPTS+1)
        DELTAY = Y(NPTS+2)
      call AXIS(1.0,1.0,XTITLE,XLEN,6.,0.,FIRSTX,DELTAX)
      call STAXIS(.15,.22,.10,.080,2)
      call AXIS(1.,1.,YTITLE,YLEN,4.,90.,FIRSTY,DELTAY)
      call SYMBOL(PTX,PTY,CHARHT,PTITLE,0.,NCHAR)
      if (PPLANE .eq. 1) then
        call SYMBOL(3.0,5.25,.18,'(',0.,1)
        call NUMBER(999.,5.25,.18,BEGTIM,0.,4)
        call SYMBOL(999.,5.25,.18,' - ',0.,3)
        call NUMBER(999.,5.25,.18,FINTIM,0.,4)
        call SYMBOL(999.,5.25,.18,' seconds)',0.,9)
      endif
      call PLOT(1.,1.,-13)
      call LINE(X,Y,NPTS,1,0,0)
      call PLOT(0.0,0.0,999)
C
      MODEL=99
      IOPORT=99
C
      RETURN
      END
C  ***********************************
C  ****** PLOTTING SUBROUTINES ******
C  ******(multi- function plot)******
C  ***********************************
      Subroutine MGRAPH(X,Y5,Y6,Y7,Y8,LINE0,DISOPT,KPWM,DBAND,
     +           X0,Y0,WFACT)
C
      implicit REAL*4 (A-Z)
      COMMON BEGTIM,FINTIM,NPTS,IOPORT,MODEL,XLEN,YLEN,PLEN,PPLANE,
     +       XTITLE,YTITLE,PTITLE
      real*4 X(1010),Y5(1010),Y6(1010),Y7(1010),Y8(1010),LINE0(1010)
      integer*2 NPTS,IOPORT,MODEL,XLEN,YLEN,PPLANE
      character*1 DISOPT
      character*3 ANS
      character*20 XTITLE,YTITLE
      character*51 PTITLE
C
C       WFACT=.5
C  ...Time axis ...
        X(NPTS+1)=BEGTIM
        FIRSTX = BEGTIM
        X(NPTS+2)=(BEGTIM-FINTIM)/10.
        DELTAX = (FINTIM-BEGTIM)/10.
C
        call SCALE(Y5,4.,NPTS,1)
        FIRSY5=Y5(NPTS+1)
        DELTY5=Y5(NPTS+2)
        LINE0(NPTS+1)=Y5(NPTS+1)
        LINE0(NPTS+2)=Y5(NPTS+2)
        Y6(NPTS+1)=-1.0
        Y6(NPTS+2)=.2
        Y7(NPTS+1)=-1.0
        Y7(NPTS+2)=.2
        Y8(NPTS+1)=-12.0
        Y8(NPTS+2)=1.
      CALL PLOTS(0,IOPORT,MODEL)
      CALL FACTOR(WFACT)
      if (DISOPT .eq. '1') then
         call PLOT(2.5,1.,-13)
      elseif (DISOPT .eq. '2') then
         call PLOT(X0/WFACT,Y0/WFACT,-13)
C ... Draw a border ...
         call PLOT(16.0,0.0,2)
```

```
          call PLOT(16.0,12.0,2)
          call PLOT(0.0,12.0,2)
          call PLOT(0.0,0.0,2)
C ... Redefine origin ...
          call PLOT(1.3,11.0,-13)
      endif
C
      CALL STAXIS(.20,.27,.16,.080,2)
      CALL AXIS(0.0,0.0,'TIME (sec)',-10,10.,270.,FIRSTX,DELTAX)
C
      CALL STAXIS(.20,.27,.16,.080,1)
      CALL AXIS(0.,0.,'ERROR SIGNAL',12,4.,0.,FIRSY5,DELTY5)
      CALL LINE(Y5,X,NPTS,1,0,0)
      CALL CURVE(LINE0,X,NPTS,-.1)
C
      CALL AXIS(5.,0.,'REFERENCE SIGNAL',16,5.,0.,0.,.2)
      CALL LINE(Y6,X,NPTS,1,0,0)
C
      CALL AXIS(5.,-10.,'THRESHOLD VOLTAGE',-17,5.,0.,0.,.2)
      CALL NEWPEN(2)
      CALL LINE(Y7,X,NPTS,1,0,0)
      CALL NEWPEN(1)
C
      CALL STAXIS(.20,.27,.13,.080,-1)
      CALL AXIS(11.,0.,'DIRECTIONAL LOGIC',17,2.,0.,-1.,1.)
      CALL LINE(Y8,X,NPTS,1,0,0)
C
      PTITLE='PWM OPEN LOOP PERFORMANCE'
      call SYMBOL(14.2,-1.3,.35,PTITLE,270.,26)
      call SYMBOL(13.6,-1.0,.3,'GAIN = ',270.,7)
      call NUMBER(13.6,999.,.3,KPWM,270.,2)
      call SYMBOL(13.6,-5.0,.3,'DEAD ZONE = ',270.,12)
      call NUMBER(13.6,999.,.3,DBAND,270.,2)
C
      CALL PLOT(0.0,0.0,999)
C
      MODEL=99
      IOPORT=99
C
      RETURN
      END
C    ****************************************************
C    ***** Cutoff-Saturation Limiting Subroutine *****
C    ****************************************************
         Subroutine LIMIT(RSAT,RCUT,INPUT,OUT)
           implicit REAL*4 (A-Z)
           if (INPUT .le. RSAT) then
             OUT=RSAT
           elseif (INPUT .ge. RCUT) then
             OUT=RCUT
           else
```

```
            OUT=INPUT
          end if
C
        return
        end
C     ****************************************
C     ***** Function Switch Subroutine *****
C     ****************************************
      Subroutine FCNSW(X1,X2,X3,X4,OUT)
        implicit REAL*4 (A-Z)
        if (X1 .lt. 0.0) then
          OUT=X2
        elseif (X1 .eq. 0.0) then
          OUT=X3
        else
          OUT=X4
        end if
C
      return
      end
C     **************************************
C     ***** Step function Subroutine *****
C     **************************************
      Subroutine STEP(TIME,TSTEP,OUT)
        implicit REAL*4 (A-Z)
        if (TIME .ge. TSTEP) then
          OUT=1.0
        else
          OUT=0.0
        end if
C
      return
      end
C     *********************************
C     ***** Deadspace Subroutine *****
C     *********************************
      Subroutine DEADSP(P1,P2,VSGDEL,VSGERR)
        implicit REAL*4 (A-Z)
        if (VSGDEL .gt. P2) then
          VSGERR=VSGDEL-P2
        elseif (VSGDEL .lt. P1) then
          VSGERR=VSGDEL-P1
        else
          VSGERR=0.0
        end if
C
      return
      end
C     ***************************
C     ***** Ramp Subroutine *****
C     ***************************
```

```
        Subroutine RAMP(TIME,TRAMP,OUT)
          implicit REAL*4 (A-Z)
          if (TIME .ge. TRAMP) then
            OUT=TIME-TRAMP
          else
            OUT=0.0
          end if
C
        return
        end
C     **********************
C     *** TIME CONSTANT ***
C     **********************
C
      Subroutine TCONST(IC,X,TAU,NTIME,NTIM,DELTIM,Y)
        implicit real*4 (A-Z)
        integer*2 NTIME,NTIM
        if (NTIME .ne. NTIM) IC=Y
        DECAY=exp(-DELTIM/TAU)
        Y=X-(X-IC)*DECAY
        if (NTIME .eq. 1) Y=IC
        NTIM=NTIME
C
      return
      end
C    **********************************************
C    ***** First Order Derivative Subroutine *****
C    **********************************************
        Subroutine DERIV(DELTIM,NTIME,NTIM1,IC2,XM1,NOWVAL,XX,XDM1,
     +                   XD,XDDM1,XDD,SLOPE)
          implicit REAL*4 (A-Z)
          integer*2 NTIME,NTIM1
C
          if (NTIME .eq. NTIM1) then
            XX=NOWVAL
          else
            XM1=XX
            XX=NOWVAL
            XDM1=XD
            XDDM1=XDD
          end if
C
          XD=(XX-XM1)/DELTIM
          if (abs(XD) .lt. 1.E-8) XD=0.
          if (NTIME .eq. 1) XD=IC2
          XDD=(XD-XDM1)/DELTIM
          if (abs(XDD) .lt. 1.E-8) XDD=0.0
C
          NTIM1=NTIME
C
          XPRED=XX+XD*DELTIM+XDD*(DELTIM**2)/2.0
          if (abs(XPRED) .lt. 1.E-8) XPRED=0.0
          SLOPE=(XPRED-XM1)/(2.0*DELTIM)
          if (abs(SLOPE) .lt. 1.E-8) SLOPE=0.0
C
         return
         end
C     ************************************************
C     ***** Trapezoidal Integration Subroutine *****
C     ************************************************
         Subroutine INTGRL(NTIME,NTIM2,DELTIM,IC3,PREVAL,NOWVAL,
     +                    CURVAL,OUTOLD,OUTNEW)
          implicit REAL*4 (A-Z)
          integer*2 NTIME,NTIM2
C
          if (NTIME .eq. NTIM2) then
            CURVAL=NOWVAL
          else
            PREVAL = CURVAL
            CURVAL = NOWVAL
            OUTOLD = OUTNEW
          end if
          if (NTIME .eq. 1) OUTOLD=IC3
          OUTNEW  = OUTOLD+(CURVAL+PREVAL)*DELTIM/2.
          NTIM2=NTIME
C
         return
         end
C     ******************************************
C     ***** CLEAR SCREEN AND HOME CURSOR *****
C     ******************************************
       subroutine CLRSCR
       character*1 C1,C2,C3,C4
       integer*2 IC(4)
       equivalence (C1,IC(1)),(C2,IC(2)),(C3,IC(3)),(C4,IC(4))
       data IC/16#1B,16#5B,16#32,16#4A/
C
C *** Write Escape Code to Display ***
       write(*,1) C1,C2,C3,C4
     1 format(1X,4A1)
C
       return
       end
C     *******************************************
C     ***** Position Cursor by Row,Column *****
C     *******************************************
       subroutine GOTOXY(ROW,COLUMN)
       integer*2 IC(4),ROW,COLUMN,L
       character*1 C1,C2,C5,C8,LC(5)
       character*5 CBUFF
       equivalence (C1,IC(1)),(C2,IC(2)),(C5,IC(3)),(C8,IC(4)),
     +           (CBUFF,LC(1))
```

```
      data IC/16#1B,16#5B,16#3B,16#66/
C
      L=10000+100*ROW+COLUMN
C
C *** Write Escape Codes to a Character Buffer ***
      write(CBUFF,2) L
    2 format(I5)
C
C *** Write Escape Codes to Display ***
      write(*,3) C1,C2,LC(2),LC(3),C5,LC(4),LC(5),C8
    3 format(1X,8A1,\)
      return
      end
```

APPENDIX C

LUMPED PARAMETER MODEL SIMULATION PROGRAM

```
$NOfloatcalls
$NOdebug
C
C       _______________________________________________
C      |                                               |
C      | ROSSITTO, VS  · THESIS    PROF GERBA  03/26/87 |
C      |_____________LINEARIZED_MODEL__________________|
C
C       This program simulates the averaged parameter model configured
C       for position control. Options are available to the user for
C       Pulse Width Modulation, Relay, or Saturating Amplifier control.
C       Step, Ramp, & Sinusoidal Responses are available. Both second
C       and third order models may be analyzed.
      IMPLICIT REAL*4 (A-Z)
      COMMON BEGTIM,FINTIM,NPTS,IOPORT,MODEL,XLEN,YLEN,PLEN,PLEN1,
     +       XTITLE,YTITLE,PTITLE,PTIT1
      REAL*4 X(1010),Y1(1010),Y2(1010),Y3(1010),Y4(1010)
      INTEGER*2 NTERMS,IOPORT,MODEL,XLEN,YLEN,NTIME,NUMIT,NTIM1,
     +          NTIM2,NTIM3,NTIM4,DIR,PMODEL,NPTS,NCTR,PPLANE,
     +          SIM2PL,ECTR,EDCTR,NUMBER,NDIM,CTR,ELEMNT,SYSORD,TEMORD
      LOGICAL*2 WAITNG,TOGGLE
      CHARACTER*1 DISOPT,PLOPT
      CHARACTER*6 ANS1,ANS11,ANS21,ANS27,PRTSEL,NONLIN
      CHARACTER*15 TYPE,TYPE1
      CHARACTER*25 XTITLE,YTITLE,NLCHAR
      CHARACTER*51 PRTCHR,PTITLE,PTIT1
C
C  ... Introductory Page (1 time good deal!)
      call CLRSCR
      write(*,4)
      PAUSE
C     ******************************************
C     *** OPEN/READ/CLOSE INPUT DATA FILE ***
C     ******************************************
C
   13 open(7,FILE='LM.INP',STATUS='OLD',ACCESS='SEQUENTIAL')
      read(7,1000) PMODEL,PRTCHR
      read(7,1020) BEGTIM,FINTIM,MAXITS,SIM2PL
      read(7,1022) KPWM,KV,E0,EDOTO
      read(7,1024) R,L,J,F,KT,KB,KP
      read(7,1026) PERIOD,DBAND,XORG,YORG
      read(7,1028) KA,SYSORD
      read(7,1030) TYPE,STPMAG,RSLOPE,SINAMP
      read(7,1032) SINFRQ,SINPHA
      close(7,STATUS='KEEP')
C
C     ****************************************
C     *** DISPLAY MAIN MENU SELECTIONS ***
C     ****************************************
C
    1 call CLRSCR
      call GOTOXY(8,1)
      write(*,5)
      read(*,'(A)') ANS1
C  ... Hardware Options ...
      if ((ANS1 .eq. 'h') .or. (ANS1 .eq. 'H')) then
C
  101    call CLRSCR
         call GOTOXY(17,24)
         write(*,*)'*** CURRENT PRINTER SELECTION ***'
         call GOTOXY(20,20)
         write(*,*) PRTCHR
         call GOTOXY(10,1)
         write(*,105)
         read(*,'(A)') ANS11
C
C  ... Printer Options ...
         if ((ANS11 .eq. 'p') .or. (ANS11 .eq. 'P')) then
  131       call CLRSCR
            write(*,130)
            read(*,'(A)') PRTSEL
C
            if (PRTSEL .eq. '0') then
               PRTCHR='Epson FX-80 Printer, single density'
               PMODEL=0
            elseif (PRTSEL .eq. '1') then
               PRTCHR='Epson FX-80 Printer, double density'
               PMODEL=1
            elseif (PRTSEL .eq. '2') then
               PRTCHR='Epson FX-80 Printer, dble spd,dual density'
               PMODEL=2
            elseif (PRTSEL .eq. '3') then
               PRTCHR='Epson FX-80 Printer, quad density'
               PMODEL=3
            elseif (PRTSEL .eq. '4') then
               PRTCHR='Epson FX-80 Printer, CRT Graphics I'
               PMODEL=4
            elseif (PRTSEL .eq. '5') then
               PRTCHR='Epson FX-80 Printer, plotter graphics'
               PMODEL=5
            elseif (PRTSEL .eq. '6') then
               PRTCHR='Epson FX-80 Printer, CRT Graphics II'
               PMODEL=6
            elseif (PRTSEL .eq. '10') then
```

```
               PRTCHR='Epson FX-100 Printer, single density'
               PMODEL=7
            elseif (PRTSEL .eq. '11') then
               PRTCHR='Epson FX-100 Printer, double density'
               PMODEL=11
            elseif (PRTSEL .eq. '12') then
               PRTCHR='Epson FX-100 Printer, dble spd,dual density'
               PMODEL=12
            elseif (PRTSEL .eq. '13') then
               PRTCHR='Epson FX-100 Printer, quad density'
               PMODEL=13
            elseif (PRTSEL .eq. '14') then
               PRTCHR='Epson FX-100 Printer, CRT Graphics I'
               PMODEL=14
            elseif (PRTSEL .eq. '15') then
               PRTCHR='Epson FX-100 Printer, plotter graphics'
               PMODEL=15
            elseif (PRTSEL .eq. '16') then
               PRTCHR='Epson FX-100 Printer, CRT Graphics II'
               PMODEL=16
            elseif (PRTSEL .eq. '20') then
               PRTCHR='HP 7470A Graphics Plotter'
               PMODEL=20
            elseif (PRTSEL .eq. '30') then
               PRTCHR='HP 7475A Graphics Plotter'
               PMODEL=30
            elseif (PRTSEL .eq. '60') then
               PRTCHR='HP 2686A Laser Jet Printer'
               PMODEL=60
C
C  ... Quit the Printer Menu ...
            elseif ((PRTSEL .eq. 'Q') .or. (PRTSEL .eq. 'q')) then
               go to 101
            else
               go to 131
            endif
            go to 101
C
C  ... Quit the Hardware Menu ...
         elseif((ANS11 .eq. 'q') .or. (ANS11 .eq. 'Q')) then
            go to 1
         else
            go to 101
         endif
C
C  ... Motor Parameters ...
      elseif ((ANS1 .eq. 'm') .or. (ANS1 .eq. 'M')) then
C
 201     call CLRSCR
         write(*,230) KT,KB,R,L,J,F,KP,KV,SYSORD
         read(*,'(A)') ANS21
```

```
C
         if (ANS21 .eq. 'KT') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for KT--> '
            read(*,*) KT
            go to 201
         elseif (ANS21 .eq. 'KB') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for KB--> '
            read(*,*) KB
            go to 201
         elseif (ANS21 .eq. 'R') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for R--> '
            read(*,*) R
            go to 201
         elseif (ANS21 .eq. 'L') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for L--> '
            read(*,*) L
            go to 201
         elseif (ANS21 .eq. 'J') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for J--> '
            read(*,*) J
            go to 201
         elseif (ANS21 .eq. 'F') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for F--> '
            read(*,*) F
            go to 201
         elseif (ANS21 .eq. 'KP') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for KP--> '
            read(*,*) KP
            go to 201
         elseif (ANS21 .eq. 'KV') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for KV--> '
            read(*,*) KV
            go to 201
         elseif (ANS21 .eq. 'SYSORD') then
            call GOTOXY(24,1)
         write(*,'(A\)')'Enter an INTEGER value (2 or 3) for SYSORD--> '
            read(*,*) TEMORD
            if ((TEMORD .ne. 2) .and. (TEMORD .ne. 3)) then
               call CLRSCR
               call GOTOXY(10,10)
               write(*,*) 'The System Order may be 2 or 3 only!!'
               call GOTOXY(22,1)
               PAUSE
            else
               SYSORD=TEMORD
            endif
            go to 201
C  ... Quit Motor Parameters Menu ...
         elseif (ANS21 .eq. 'Q') then
            go to 1
         else
            go to 201
         end if
C
C  ... NON-LINEAR ELEMENT SELECTION MENU ...
C
        elseif ((ANS1 .eq. 'n') .or. (ANS1 .eq. 'N')) then
  14     call CLRSCR
         call GOTOXY(21,1)
         write(*,272) NLCHAR
         call GOTOXY(1,1)
         write(*,270)
         read(*,'(A)') ANS27
C  ... RELAY AS NON-LINEAR ELEMENT ...
         if ((ANS27 .eq. 'r') .or. (ANS27 .eq. 'R')) then
            ELEMNT=1
            NLCHAR='RELAY'
 291        call CLRSCR
            NONLIN='R'
            write(*,290) DBAND
            read(*,'(A)') ANS21
C
           if (ANS21 .eq. 'DBAND') then
              call GOTOXY(24,1)
              write(*,'(A\)')'Enter a REAL value for DBAND--> '
              read(*,*) DBAND
              go to 291
           elseif ((ANS21 .eq. 'q') .or. (ANS21 .eq. 'Q')) then
              go to 14
           else
              go to 291
           endif
C  ... PULSE WIDTH MODULATOR AS NON-LINEAR ELEMENT ...
         elseif ((ANS27 .eq. 'p') .or. (ANS27 .eq. 'P')) then
            ELEMNT=3
            NLCHAR='PULSE WIDTH MODULATOR'
 301        call CLRSCR
            NONLIN='P'
            write(*,300) DBAND,PERIOD,KPWM
            read(*,'(A)') ANS21
C
           if (ANS21 .eq. 'DBAND') then
              call GOTOXY(24,1)
              write(*,'(A\)')'Enter a REAL value for DBAND--> '
```

```
               read(*,*) DBAND
               go to 301
            elseif (ANS21 .eq. 'PERIOD') then
               call GOTOXY(24,1)
               write(*,'(A\)')'Enter a REAL value for PERIOD--> '
               read(*,*) PERIOD
               go to 301
            elseif (ANS21 .eq. 'KPWM') then
               call GOTOXY(24,1)
               write(*,'(A\)')'Enter a REAL value for KPWM--> '
               read(*,*) KPWM
               go to 301
            elseif ((ANS21 .eq. 'q') .or. (ANS21 .eq. 'Q')) then
               go to 14
            else
               go to 301
            endif
C
C  ... SATURATING AMPLIFIER AS NON-LINEAR ELEMENT ...
           elseif ((ANS27 .eq. 'a') .or. (ANS27 .eq. 'A')) then
              ELEMNT=2
              NLCHAR='SATURATING AMPLIFIER'
  281         call CLRSCR
              NONLIN='A'
              write(*,280) DBAND,KA
              read(*,'(A)') ANS21
C
            if (ANS21 .eq. 'DBAND') then
               call GOTOXY(24,1)
               write(*,'(A\)')'Enter a REAL value for DBAND--> '
               read(*,*) DBAND
               go to 281
            elseif (ANS21 .eq. 'KA') then
               call GOTOXY(24,1)
               write(*,'(A\)')'Enter a REAL value for KA--> '
               read(*,*) KA
               go to 281
            elseif ((ANS21 .eq. 'q') .or. (ANS21 .eq. 'Q')) then
               go to 14
            else
               go to 281
            endif
C
           elseif ((ANS27 .eq. 'q') .or. (ANS27 .eq. 'Q')) then
              go to 1
           else
              go to 14
           endif
C
C  ... Simulation Options ...
      elseif ((ANS1 .eq. 'o') .or. (ANS1 .eq. 'O')) then
```

```
C
 202     call CLRSCR
C
         DELTIM=(FINTIM-BEGTIM)/(1000.*SIM2PL)
         if (FINTIM/DELTIM .gt. MAXITS) DELTIM =FINTIM/MAXITS
         NTERMS=IFIX(FINTIM/DELTIM)+1
C
         write(*,240) BEGTIM,FINTIM,MAXITS,SIM2PL,E0,EDOT0,XORG,YORG,
     +                DELTIM,NTERMS
         read(*,'(A)') ANS21
C
         if (ANS21 .eq. 'BEGTIM') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for BEGTIM--> '
            read(*,*) BEGTIM
            go to 202
         elseif (ANS21 .eq. 'FINTIM') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for FINTIM--> '
            read(*,*) FINTIM
            go to 202
         elseif (ANS21 .eq. 'MAXITS') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for MAXITS--> '
            read(*,*) MAXITS
            go to 202
         elseif (ANS21 .eq. 'SIM2PL') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a INTEGER value for SIM2PL--> '
            read(*,*) SIM2PL
            go to 202
         elseif (ANS21 .eq. 'E0') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for E0 (degrees)--> '
            read(*,*) E0
            go to 202
         elseif (ANS21 .eq. 'EDOT0') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for EDOT0 (deg/sec)--> '
            read(*,*) EDOT0
            go to 202
         elseif (ANS21 .eq. 'XORG') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for XORG--> '
            read(*,*) XORG
            go to 202
         elseif (ANS21 .eq. 'YORG') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for YORG--> '
            read(*,*) YORG
            go to 202
```

```
C  ... Quit Simulation Options Menu ...
         elseif (ANS21 .eq. 'Q') then
            go to 1
         else
            go to 202
         end if
C
C  ... Command Input Selection ...
      elseif ((ANS1 .eq. 'c') .or. (ANS1 .eq. 'C')) then
C
 203     call CLRSCR
C
         write(*,245) TYPE,STPMAG,RSLOPE,SINAMP,SINFRQ,SINPHA
         read(*,'(A)') ANS21
C
         if (ANS21 .eq. 'TYPE') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a STEP, RAMP, or SINE--> '
            read(*,'(A)') TYPE1
            if ((TYPE1 .ne. 'STEP') .and. (TYPE1 .ne. 'RAMP') .and.
     +           (TYPE1 .ne. 'SINE')) then
               call CLRSCR
               call GOTOXY(10,10)
               write(*,*) 'Invalid Selection !!!'
               call GOTOXY(20,1)
               PAUSE
               go to 203
            else
               TYPE=TYPE1
            endif
C
            go to 203
         elseif (ANS21 .eq. 'STPMAG') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for STPMAG--> '
            read(*,*) STPMAG
            go to 203
         elseif (ANS21 .eq. 'RSLOPE') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for RSLOPE--> '
            read(*,*) RSLOPE
            go to 203
         elseif (ANS21 .eq. 'SINAMP') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for SINAMP--> '
            read(*,*) SINAMP
            go to 203
         elseif (ANS21 .eq. 'SINFRQ') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for SINFRQ--> '
            read(*,*) SINFRQ
            go to 203
         elseif (ANS21 .eq. 'SINPHA') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for SINPHA--> '
            read(*,*) SINPHA
            go to 203
C   ... Quit Simulation Options Menu ...
         elseif (ANS21 .eq. 'Q') then
            go to 1
         else
            go to 203
         end if
C   ... Save Options to File ...
      elseif ((ANS1 .eq. 's') .or. (ANS1 .eq. 'S')) then
C
C     ******************************************
C     *** OPEN/WRITE/CLOSE INPUT DATA FILE ***
C     ******************************************
C
         open(7,FILE='LM.INP',STATUS='NEW')
            write(7,1000) PMODEL,PRTCHR
            write(7,1020) BEGTIM,FINTIM,MAXITS,SIM2PL
            write(7,1022) KPWM,KV,E0,EDOT0
            write(7,1024) R,L,J,F,KT,KB,KP
            write(7,1026) PERIOD,DBAND,XORG,YORG
            write(7,1028) KA,SYSORD
            write(7,1030) TYPE,STPMAG,RSLOPE,SINAMP
            write(7,1032) SINFRQ,SINPHA
            write(7,2000)
         close(7,STATUS='KEEP')
C
        go to 1
C
C   ... Run the Program ...
      elseif ((ANS1 .eq. 'r') .or. (ANS1 .eq. 'R')) then
         go to 2
C
C   ... Quit the Program ...
      elseif ((ANS1 .eq. 'q') .or. (ANS1 .eq. 'Q')) then
        stop
      else
        go to 1
      endif
C
C   ... Open an Output Data File ...
   2  open(4,FILE='LM.OUT',STATUS='NEW')
C
      PI=3.14159
      N=.1
C
C   ... Initializations ...
```

```
      NCTR=0
      NPTS=0
      NTIM2=1
      NTIM3=0
      NTIM4=0
      PARG1=0.0
      PARG2=0.0
      PVAL4=0.
      CARG1=0.0
      CARG2=0.0
      CVAL4=0.
      TOT1=0.0
      TOT2=0.0
      TVAL1=0.0
      TVAL2=0.0
      TVAL4=0.
      XM1=0.0
      XX=0.0
      XDM1=0.0
      XD=0.0
      XDDM1=0.0
      XDD=0.0
      X1=0.0
      F1=0.0
      F2=0.0
      X3=0.0
      WM1=0.0
      WM=0.0
      IM=0.
      IM0=0.
      TSTART=0.0
      THEDEG=0.0
      TOGGLE=.true.
      PPLANE=0
      NUMBER=0
      NDIM=20
      VIN=0.
C
C  ... Preliminary Relationships ...
C  ... Initial conditions for THETA(fin,degrees) and Omega(fin,degrees).
      E0RAD=10.*E0*PI/180.
      EDOT0R=10.*EDOT0*PI/180.
      if (KP .ne. 0.) then
         WM0=-EDOT0R/KP
         THETA0=-E0RAD/KP
      elseif (KP .eq. 0.) then
         WM0=-EDOT0R
         THETA0=-E0RAD
      endif
      IM0=(VIN-WM0*KB)/R
      X2=WM0
      PTHETA=THETA0
      TAU1=L/R
      TAU2=J/F
C
      call CLRSCR
C  ... Output Simulation Options to Output Data File ...
      write(4,1200) SYSORD,BEGTIM,FINTIM,MAXITS,SIM2PL,KT,KB,R,L,J,F,KP,
     +              KV,KA,PERIOD,DBAND,E0,EDOT0
      write(4,1201) TYPE,STPMAG,RSLOPE,SINAMP,SINFRQ,SINPHA
C
C ... Display the simulation header ...
      call CLRSCR
      call GOTOXY(10,27)
      write(*,*) 'Simulation in Progress'
      DELTIM=(FINTIM-BEGTIM)/(1000.*SIM2PL)
      if (FINTIM/DELTIM .gt. MAXITS) DELTIM =FINTIM/MAXITS
      NTERMS=IFIX(FINTIM/DELTIM)+1
      call GOTOXY(14,1)
      write(*,15) DELTIM,NTERMS
   15 format(16X,'Simulation Step Size --> ',F9.8,' seconds',/,
     +       17X,'Total Number of Steps--> ',I5)
      call GOTOXY(21,1)
C
      if ((NONLIN .eq. 'r') .or. (NONLIN .eq. 'R')) then
       write(*,*) '                 *** NON-LINEAR ELEMENT IS RELAY ***'
      elseif ((NONLIN .eq. 'a') .or. (NONLIN .eq. 'A')) then
       write(*,*) '           *** NON-LINEAR ELEMENT IS SATURATING AMPLI
     +FIER ***'
      elseif ((NONLIN .eq. 'p') .or. (NONLIN .eq. 'P')) then
       write(*,*) '                 *** NON-LINEAR ELEMENT IS PWM ***'
      else
       write(*,*) '            *** NON-LINEAR ELEMENT NOT SELECTED ***'
       write(*,*) '                  ... Return to Main Menu ...'
       PAUSE
       go to 1
      endif
C
      SPACE=DELTIM/2.0
C
C     ***********************************
C     *** START MAIN SIMULATION LOOP ***
C     ***********************************
C
      DO 100 NTIME=1,NTERMS
        TIME=(NTIME-1)*DELTIM
        NUMIT=0
        THETA=PTHETA
C
C     ************************************
C     *** START INNER SIMULATION LOOP ***
C     ************************************
```

```
C
 200    NUMIT=NUMIT+1
        WM=X2
C
C  ... Command Input Signal Generator ...
         if (TYPE .eq. 'STEP') then
            ORDER=STPMAG
         elseif (TYPE .eq. 'RAMP') then
            ORDER=RSLOPE*TIME
         elseif (TYPE .eq. 'SINE') then
            ORDER=SINAMP*sin(SINFRQ*TIME+SINPHA)
         endif
C
        THETAF=.1*THETA*180./PI
        OMEGAF=.1*WM*180./PI
        POSERR=ORDER-KP*THETAF-KV*OMEGAF
C
C  ... Utilization of Non-Linear Element ...
C  ... PULSE WIDTH MODULATOR ...
      if ((NONLIN .eq. 'p') .or. (NONLIN .eq. 'P')) then
         call PWMOD(TIME,NUMIT,TSTART,PERIOD,TOGGLE,POSERR,
     +              DBAND,VIN,VREF,THRESH,KPWM)
C  ... IDEAL RELAY ...
      elseif ((NONLIN .eq. 'r') .or. (NONLIN .eq. 'R')) then
         call RELAY(POSERR,DBAND,VIN)
C  ... SATURATING AMPLIFIER ...
      elseif ((NONLIN .eq. 'a') .or. (NONLIN .eq. 'A')) then
         call AMPLIF(POSERR,DBAND,KA,VIN)
      else
         call GOTOXY(21,1)
         write(*,*) '          *** NON-LINEAR ELEMENT NOT SELECTED ***'
         write(*,*) '                ... Return to Main Menu ...'
         PAUSE
         go to 1
      endif
C
        EN=VIN-WM*KB
C
        if (SYSORD .eq. 3) then
           call TCONST(IM0,EN/R,TAU1,NTIME,NTIM1,DELTIM,IM)
        elseif (SYSORD .eq. 2) then
           IM=EN/R
        else
           call CLRSCR
           call GOTOXY(10,10)
           write(*,*) 'SYSTEM ORDER IS NOT 2 OR 3!!'
           PAUSE
           go to 1
        endif
C
        TM=IM*KT
        call TCONST(WM0,TM/F,TAU2,NTIME,NTIM2,DELTIM,WM1)
      call INTGRL(NTIME,NTIM4,DELTIM,THETA0,PVAL4,WM1,CVAL4,TVAL4,THET1)
        THETA=THET1
C
C     **************************************************
C     *** CONVERGENCE CRITERIA (Newton's Method) ***
C     **************************************************
C
      if (NTIME .eq. 1) then
        X3=WM1
        F2=0.
        go to 150
      end if
C
      if (NUMIT .eq. 1) then
        F2=(WM1-WM)*1.2
        X3=1.001*WM1+1.0E-4
        RELERR=abs(F2/X3)
        go to 310
      end if
C
      F2=WM1-WM
      if (F1 .eq. F2) F2=.999*F2-1.E-8
      if (X2 .ne. 0.) RELERR=abs(F2/X2)
      if (X2 .eq. 0.) RELERR=1.
      if (RELERR .gt. 1.E-8) then
         X3=X2-F2*(X1-X2)/(F1-F2)
      endif
  310 X1=X2
      X2=X3
      F1=F2
C
      WM=X2
C
      if (NUMIT .ge. 10) go to 150
      if (RELERR .gt. 1.E-8) go to 200
C
C     ***********************************
C     *** END INNER SIMULATION LOOP ***
C     ***********************************
C
  150 call DERIV(DELTIM,NTIME,NTIM3,0.,XM1,WM1,XX,XDM1,XD,XDDM1,XDD,
     +            ALPHA)
C
      X2=WM1+ALPHA*DELTIM
      PTHETA=THETA+WM1*DELTIM
      THETAF=.1*THETA*180./PI
      OMEGAF=.1*WM1*180./PI
C
C  ... Generate Plotting Arrays ...
      if (TIME .ge. BEGTIM) then
```

```
          NCTR=NCTR+1
          if ((mod(NCTR,SIM2PL) .eq. 0) .or. (NCTR .eq. 1)) then
            NPTS=NPTS+1
            X(NPTS)=TIME
            Y1(NPTS)=THETAF
            Y2(NPTS)=OMEGAF
            Y3(NPTS)=ORDER
            Y4(NPTS)=IM
          endif
        endif
C
  100 CONTINUE
C
C     **********************************
C     *** END MAIN SIMULATION LOOP ***
C     **********************************
C
      close(4,STATUS='KEEP')
C
C     ******************************
C     ***** Plotting selection *****
C     ******************************
C
C *** Clear Screen & Home Cursor ***
  400 call CLRSCR
C
      write(*,1305)
      read(*,'(A)') DISOPT
C
      if ((DISOPT .eq. 'm') .or. (DISOPT .eq. 'M')) then
        MODEL=99
        IOPORT=99
      elseif ((DISOPT .eq. 'p') .or. (DISOPT .eq. 'P')) then
        MODEL=PMODEL
        IOPORT=1
C  ... Ioport=9600 is COM1 ...
C  ... Ioport=9650 is COM2 ...
        if ((MODEL .eq. 20) .or. (MODEL .eq. 30)) IOPORT=9600
      elseif ((DISOPT .eq. 'r') .or. (DISOPT .eq. 'R')) then
        GO TO 13
      elseif ((DISOPT .eq. 's') .or. (DISOPT .eq. 'S')) then
C
C     ****************************************
C     *** OPEN/WRITE/CLOSE INPUT DATA FILE ***
C     ****************************************
C
         open(7,FILE='LM.INP',STATUS='NEW')
            write(7,1000) PMODEL,PRTCHR
            write(7,1020) BEGTIM,FINTIM,MAXITS,SIM2PL
            write(7,1022) KPWM,KV,E0,EDOT0
            write(7,1024) R,L,J,F,KT,KB,KP
          write(7,1026) PERIOD,DBAND,XORG,YORG
          write(7,1028) KA,SYSORD
          write(7,1030) TYPE,STPMAG,RSLOPE,SINAMP
          write(7,1032) SINFRQ,SINPHA
          write(7,2000)
        close(7,STATUS='KEEP')
C
         go to 400
C
      elseif ((DISOPT .eq. 'Q') .or. (DISOPT .eq. 'q')) then
        GO TO 460
      else
        go to 400
      end if
C
  410 call CLRSCR
      if ((DISOPT .eq. 'p') .or. (DISOPT .eq. 'P')) then
        call GOTOXY(20,20)
        write(*,*) PRTCHR
        call GOTOXY(1,1)
      endif
      write(*,1300)
      read(*,'(A)') PLOPT
C
      if ((PLOPT .eq. 'Q') .or. (PLOPT .eq. 'q')) then
        go to 400
      elseif (PLOPT .eq. '1') then
           XTITLE='TIME (seconds)'
           XLEN=-15
           YTITLE='FIN POSITION (deg)'
           YLEN=19
         if (ELEMNT .eq. 1) then
           PTITLE='FIN POSITION RESPONSE WITH RELAY CONTROLLER'
           PLEN=44.
         elseif (ELEMNT .eq. 2) then
           PTITLE='FIN POSITION RESPONSE WITH SAT AMP CONTROLLER'
           PLEN=46.
         elseif (ELEMNT .eq. 3) then
           PTITLE='FIN POSITION RESPONSE WITH PWM CONTROLLER'
           PLEN=42.
         endif
C
         if (SYSORD .eq. 2) then
           PTIT1='REDUCED ORDER MODEL'
           PLEN1=20.
         else
           PTIT1='THIRD ORDER MODEL'
           PLEN1=18.
         endif
C
         call MGRAPH(X,Y1,Y3,XORG,YORG,DISOPT)
```

```
C
      elseif (PLOPT .eq. '2') then
            XTITLE='TIME (seconds)'
            XLEN=-15
            YTITLE='FIN VELOCITY (deg/sec)'
            YLEN=23
         if (ELEMNT .eq. 1) then
            PTITLE='FIN VELOCITY RESPONSE WITH RELAY CONTROLLER'
            PLEN=44.
         elseif (ELEMNT .eq. 2) then
            PTITLE='FIN VELOCITY RESPONSE WITH SAT AMP CONTROLLER'
            PLEN=46.
         elseif (ELEMNT .eq. 3) then
            PTITLE='FIN VELOCITY RESPONSE WITH PWM CONTROLLER'
            PLEN=42.
         endif
C
         if (SYSORD .eq. 2) then
            PTIT1='REDUCED ORDER MODEL'
            PLEN1=20.
         else
            PTIT1='THIRD ORDER MODEL'
            PLEN1=18.
         endif
C
         call GRAPH(X,Y2,XORG,YORG,DISOPT)
C
      elseif (PLOPT .eq. '3') then
            XTITLE='TIME (seconds)'
            XLEN=-15
            YTITLE='MOTOR CURRENT (amps)'
            YLEN=20
         if (ELEMNT .eq. 1) then
            PTITLE='MOTOR CURRENT RESPONSE WITH RELAY CONTROLLER'
            PLEN=45.
         elseif (ELEMNT .eq. 2) then
            PTITLE='MOTOR CURRENT RESPONSE WITH SAT AMP CONTROLLER'
            PLEN=47.
         elseif (ELEMNT .eq. 3) then
            PTITLE='MOTOR CURRENT RESPONSE WITH PWM CONTROLLER'
            PLEN=43.
         endif
C
         if (SYSORD .eq. 2) then
            PTIT1='REDUCED ORDER MODEL'
            PLEN1=20.
         else
            PTIT1='THIRD ORDER MODEL'
            PLEN1=18.
         endif
C
```

```
           call GRAPH(X,Y4,XORG,YORG,DISOPT)
C
        else
          go to 410
        endif
C
        go to 400
  460 continue
C
C       ******************************
C       *** I/O FORMAT STATEMENTS ***
C       ******************************
C
    4 format(////,25X,'LUMPED PARAMETER DC MOTOR SIMULATION',//,
     +            25X,'     LT Vincent S. Rossitto,USN',/,
     +            25X,'      Naval Postgraduate School',/,
     +            25X,'             March 1987',//////)
C
   5  format(32X,'*** MAIN MENU ***',//,
     +       20X,'[H]----> HARDWARE Configuration Menu',/,
     +       20X,'[M]----> MOTOR Parameter Menu',/,
     +       20X,'[N]----> NON-LINEAR Element Selection Menu',/,
     +       20X,'[O]----> OPTIONS for Simulation',/,
     +       20X,'[C]----> COMMAND Input Selection Menu',/,
     +       20X,'[S]----> SAVE All Changes',/,
     +       20X,'[R]----> RUN Simulation Program',/,
     +       20X,'[Q]----> QUIT the Program',//,
     +        8X,'ENTER SELECTION---->',\)
C
 105     format(30X,'*** HARDWARE MENU ***',//,
     +       20X,'[P]----> PRINTER/PLOTTER configuration change',/,
     +       20X,'[Q]----> QUIT THIS MENU',//,
     +        8X,'ENTER SELECTION---->',\)
 1000 format(1X,I3,2X,A50)
 1020 format(1x,3F15.7,1X,I3)
 1022 format(1X,4F15.7)
 1024 format(1X,7F8.4)
 1026 format(1X,4F8.4)
 1028 format(1X,F12.7,1X,I1)
 1030 format(1X,A15,3F15.7)
 1032 format(1X,2F15.7)
 2000 format(1X,'END OF FILE')
C
 130  FORMAT(24X,'*** PRINTER OPTIONS MENU ***',//,
     +  15X,'[0] --> Epson FX-80 Printer, single density',/,
     +  15X,'[1] --> Epson FX-80 Printer, double density',/,
     +  15X,'[2] --> Epson FX-80 Printer, dble spd,dual density',/,
     +  15X,'[3] --> Epson FX-80 Printer, quad density',/,
     +  15X,'[4] --> Epson FX-80 Printer, CRT Graphics I',/,
     +  15X,'[5] --> Epson FX-80 Printer, plotter graphics',/,
     +  15X,'[6] --> Epson FX-80 Printer, CRT Graphics II',/,
     +  15X,'[10] -> Epson FX-100 Printer, single density',/,
     +  15X,'[11] -> Epson FX-100 Printer, double density',/,
     +  15X,'[12] -> Epson FX-100 Printer, dble spd,dual density',/,
     +  15X,'[13] -> Epson FX-100 Printer, quad density',/,
     +  15X,'[14] -> Epson FX-100 Printer, CRT Graphics I',/,
     +  15X,'[15] -> Epson FX-100 Printer, plotter graphics',/,
     +  15X,"[16] -> Epson FX-100 Printer, CRT Graphics II',/,
     +  15X,'[20] -> HP 7470A Graphics Plotter',/,
     +  15X,'[30] -> HP 7475A Graphics Plotter',/,
     +  15X,'[60] -> HP 2686A Laser Jet Printer (NPS installation)',/,
     +  15X,'[Q] -->   QUIT THIS MENU',//,
     +  3X,'Enter Printer Selection Integer or Q to QUIT ---> ',\)
C
 230  format(12X,'*** MOTOR PARAMETER SETTINGS MENU ***',//,
     + 4X,F12.7,1X,'[KT]      Motor Torque Constant',/,
     + 4X,F12.7,1X,'[KB]      Motor Back EMF Constant',/,
     + 4X,F12.7,1X,'[R]       Motor Equivalent Resistance (ohms)',/,
     + 4X,F12.7,1X,'[L]       Motor Inductance (henries)',/,
     + 4X,F12.7,1X,'[J]       Motor Inertia (oz-in/s^2)',/,
     + 4X,F12.7,1X,'[F]       Motor Viscous Friction Coeff',/,
     + 4X,F12.7,1X,'[KP]      Motor Position Feedback Constant',/,
     + 4X,F12.7,1X,'[KV]      Motor Velocity Feedback Constant',/,
     + 15X,I1,1X,'[SYSORD] System Order (2=Reduced;3=Linearized)',/,
     + 17X,'[Q]      QUIT THIS MENU',//,
     + 1X,'Enter variable name (UPPERCASE) or Q to QUIT ---> ',\)
C
 240  format(12X,'*** SIMULATION OPTIONS MENU ***',//,
     + 1X,F15.7,1X,'[BEGTIM]  Start Time of Plotting Window',/,
     + 1X,F15.7,1X,'[FINTIM]  Stop Time of Plotting Window',/,
     + 1X,F15.7,1X,'[MAXITS]  Max Number of Simulation Iterations',/,
     + 13X,I3,1X,'[SIM2PL]  Ratio: Points Simulated/Plotted',/,
     + 1X,F15.7,1X,'[E0]      Initial Fin Position (deg)',/,
     + 1X,F15.7,1X,'[EDOT0]   Initial Fin Velocity (deg/s)',/,
     + 1X,F15.7,1X,'[XORG]    X Coordinate of Plotting Origin',/,
     + 1X,F15.7,1X,'[YORG]    Y Coordinate of Plotting Origin',/,
     + 17X,'[Q]        QUIT THIS MENU',///,
     + 15X,'Computed simulation step size ---> ',F9.8, 'seconds',/,
     + 15X,'Computed total number of steps---> ',I5,//,
     + 1X,'Enter variable name (UPPERCASE) or Q to QUIT ---> ',\)
C
 245  format(12X,'*** COMMAND INPUT SELECTION MENU ***',//,
     + 1X,A15,1X,'[TYPE]    STEP, RAMP, or SINE Response',/,
     + 1X,F15.7,1X,'[STPMAG]  Commanded Position for STEP Response',/,
     + 1X,F15.7,1X,'[RSLOPE]  Slope of RAMP Function',/,
     + 1X,F15.7,1X,'[SINAMP]  Amplitude of SINE Function',/,
     + 1X,F15.7,1X,'[SINFRQ]  Frequency (deg/sec) of SINE Function',/,
     + 1X,F15.7,1X,'[SINPHA]  Phase Angle (deg) of SINE Function',/,
     + 17X,'[Q]        QUIT THIS MENU',///,
     + 1X,'Enter variable name (UPPERCASE) or Q to QUIT ---> ',\)
C
 270  format(///,8X,'*** NON-LINEAR ELEMENT SELECTION ***',//,
     + 10X,'[R]    Relay (Bang-Bang)',/,
     + 10X,'[P]    Pulse Width Modulator',/,
     + 10X,'[A]    Amplifier (Saturating)',/,
     + 10X,'[Q]    QUIT THIS MENU/RETURN TO MAIN MENU',//,
     + 1X,'Enter Selection ---> ',\)
C
 272  format(10X,'CURRENT SELECTION --> ',A30)
C
 280  format(///,8X,'*** SATURATING AMPLIFIER SPECIFICATIONS ***',//,
     + 1X,F15.7,1X,'[DBAND]   Deadband Applied to System Feedback',/,
     + 1X,F15.7,1X,'[KA]      Amplifier Gain',/,
     + 17X,'[Q]       QUIT THIS MENU',//,
     + 1X,'Enter the selection (UPPERCASE) ---> ',\)
C
 290  format(///,15X,'*** RELAY SPECIFICATIONS ***',//,
     + 1X,F15.7,1X,'[DBAND]   Deadband Applied to System Feedback',/,
     + 17X,'[Q]       QUIT THIS MENU',//,
     + 1X,'Enter the selection (UPPERCASE) ---> ',\)
C
 300  format(///,5X,'*** PULSE WIDTH MODULATOR SPECIFICATIONS ***',//,
     + 1X,F15.7,1X,'[DBAND]   Deadband Applied to System Feedback',/,
     + 1X,F15.7,1X,'[PERIOD]  Period of PWM Reference Cycle(sec)',/,
     + 1X,F15.7,1X,'[KPWM]    PWM Amplifier Gain',/,
     + 17X,'[Q]       QUIT THIS MENU',//,
     + 1X,'Enter the selection (UPPERCASE) ---> ',\)
C
 1200 format(20X,'LINEAR MODEL OF BRUSHLESS DC MOTOR',//,
     + 15X,I1,1X,'[SYSORD]  System Order (2=Reduced;3=Linearized)',/,
     + 1X,F15.7,1X,'[BEGTIM]  Start Time of Plotting Window',/,
     + 1X,F15.7,1X,'[FINTIM]  Stop Time of Plotting Window',/,
     + 1X,F15.7,1X,'[MAXITS]  Max Number of Simulation Iterations',/,
     + 13X,I3,1X,'[SIM2PL]  Ratio: Points Simulated/Plotted',/,
     + 4X,F12.7,1X,'[KT]      Motor Torque Constant',/,
     + 4X,F12.7,1X,'[KB]      Motor Back EMF Constant',/,
     + 4X,F12.7,1X,'[R]       Motor Equivalent Resistance (ohms)',/,
     + 4X,F12.7,1X,'[L]       Motor Inductance (henries)',/,
     + 4X,F12.7,1X,'[J]       Motor Inertia (oz-in/s^2)',/,
     + 4X,F12.7,1X,'[F]       Motor Viscous Friction Coeff',/,
     + 4X,F12.7,1X,'[KP]      Motor Position Feedback Constant',/,
     + 4X,F12.7,1X,'[KV]      Motor Velocity Feedback Constant',/,
     + 4X,F12.7,1X,'[KA]      Saturating Amplifier Gain (if used)',/,
     + 4X,F12.7,1X,'[PERIOD]  Period of PWM Reference Cycle',/,
     + 4X,F12.7,1X,'[DBAND]   Position Feedback Deadband',/,
     + 1X,F15.7,1X,'[E0]      Initial Fin  Position (deg)',/,
     + 1X,F15.7,1X,'[EDOT0]   Initial Fin Velocity (deg/s)')
C
 1201 format(1X,A15,1X,'[TYPE]    STEP, RAMP, or SINE Response',/,
     + 1X,F15.7,1X,'[STPMAG]  Commanded Position for STEP Response',/,
     + 1X,F15.7,1X,'[RSLOPE]  Slope of RAMP Function',/,
     + 1X,F15.7,1X,'[SINAMP]  Amplitude of SINE Function',/,
     + 1X,F15.7,1X,'[SINFRQ]  Frequency (deg/sec) of SINE Function',/,
     + 1X,F15.7,1X,'[SINPHA]  Phase Angle (deg) of SINE Function')
C
 1205 FORMAT(1X,F8.6,1X,1P5E12.3)
 1300 FORMAT(/////,2X,'The following are plotting options',//,
     +           5X,'[1] FIN POSITION response',/,
     +           5X,'[2] FIN VELOCITY response',/,
     +           5X,'[3] MOTOR CURRENT response',/,
     +           5X,'[Q] QUIT THIS MENU',//,
     +           2X,'Enter selection [1,Q] ---> ',\)
C
 1305 FORMAT(/////,2X,'Display options:',/,
     +           5X,'[M] MONITOR',/,
     +           5X,'[P] PRINTER',/,
     +           5X,'[R] RETURN TO START-UP MENU (RE-INITIALIZE)',/,
     +           5X,'[S] SAVE SIMULATION SPECIFICATIONS TO DISK',/,
     +           5X,'[Q] QUIT THE PROGRAM',//,
     +           2X,'Enter selection [1,2,3,Q] ---> ',\)
C
 1500 format(1X,I3,2X,A50)
C
      STOP
      END
C -----------------------------------------------------------------
C  *********************************
C  ***** PLOTTING SUBROUTINES *****
C  *****(single function plot)*****
C  *********************************
      Subroutine GRAPH(X,Y,XORG,YORG,DISOPT)
C
      implicit REAL*4 (A-Z)
      COMMON BEGTIM,FINTIM,NPTS,IOPORT,MODEL,XLEN,YLEN,PLEN,PLEN1,
     +       XTITLE,YTITLE,PTITLE,PTIT1
      real*4 X(1010),Y(1010)
      integer*2 NPTS,IOPORT,MODEL,XLEN,YLEN,NCHAR,NCHAR1
      character*1 DISOPT,ANS
      character*25 XTITLE,YTITLE
      character*51 PTITLE,PTIT1
C
C ... Make a new title...
    5 call CLRSCR
      if ((DISOPT .eq. 'P') .or. (DISOPT .eq. 'p')) then
         call GOTOXY(8,30)
         write(*,*) 'Current Title is:'
         call GOTOXY(10,20)
         write(*,*) PTITLE
         call GOTOXY(11,20)
         write(*,*) PTIT1
         call GOTOXY(15,25)
         write(*,'(A\)') 'Do you want to change the title? '
         read(*,'(A)') ANS
         call CLRSCR
```

```
            if ((ANS .eq. 'Y') .or. (ANS .eq. 'y')) then
                call GOTOXY(5,10)
             write(*,*) 'Enter titles in left justified format'
                call GOTOXY(12,10)
             write(*,*) '12345678901234567890123456789012345678901234567890'
                call GOTOXY(13,10)
             write(*,*) '         1         2         3         4         5'
                call GOTOXY(15,25)
             write(*,*) '# of characters -->'
                call GOTOXY(20,10)
             write(*,*) '12345678901234567890123456789012345678901234567890'
                call GOTOXY(21,10)
             write(*,*) '         1         2         3         4         5'
                call GOTOXY(23,25)
             write(*,*) '# of characters -->'
                call GOTOXY(11,11)
             read(*,'(A51)') PTITLE
                call GOTOXY(15,46)
             read(*,*) PLEN
                call GOTOXY(19,11)
             read(*,'(A51)') PTIT1
                call GOTOXY(23,46)
             read(*,*) PLEN1
            elseif ((ANS .eq. 'N') .or. (ANS .eq. 'n')) then
                go to 10
            endif
             go to 5
          endif
C
   10     call GOTOXY(10,25)
          write(*,*) 'Calculating Plotting Data'
C
          ASPRAT=.65
          CHARHT=.22
          CHARH1=.20
          PTX=.5+(6.-PLEN*ASPRAT*CHARHT)/2.
          PTY=4.5
          PTX1=.5+(6.-PLEN1*ASPRAT*CHARH1)/2.
          PTY1=4.1
          NCHAR=ifix(PLEN)
          NCHAR1=ifix(PLEN1)
C
          call PLOTS(0,IOPORT,MODEL)
          call FACTOR(1.00)
          call ASPECT(ASPRAT)
C ...     Draw a Border
          if ((DISOPT .eq. 'P') .or. (DISOPT .eq. 'p')) then
             call PLOT(XORG,YORG,-13)
              call PLOT(8.0,0.0,2)
              call PLOT(8.0,6.0,2)
              call PLOT(0.0,6.0,2)
          call PLOT(0.0,0.0,2)
         call PLOT(1.25,1.,-13)
      elseif ((DISOPT .eq. 'M') .or. (DISOPT .eq. 'm')) then
         call PLOT(1.,1.,-13)
      endif
C
C  ... This scaling applies when the X axis represents Time...
      X(NPTS+1)=BEGTIM
      FIRSTX = X(NPTS+1)
      X(NPTS+2)=(X(NPTS)-X(NPTS+1))/6.
      DELTAX = X(NPTS+2)
C
      call SCALE(Y,4.,NPTS,1)
      FIRSTY = Y(NPTS+1)
      DELTAY = Y(NPTS+2)
      call STAXIS(.15,.22,.12,.080,3)
      call AXIS(0.0,0.0,XTITLE,XLEN,6.,0.,FIRSTX,DELTAX)
      call STAXIS(.15,.22,.12,.080,2)
      call AXIS(0.,0.,YTITLE,YLEN,4.,90.,FIRSTY,DELTAY)
      call SYMBOL(PTX,PTY,CHARHT,PTITLE,0.,NCHAR)
      call SYMBOL(PTX1,PTY1,CHARH1,PTIT1,0.,NCHAR1)
      call LINE(X,Y,NPTS,1,0,0)
      call PLOT(0.,0.,999)
C
      MODEL=99
      IOPORT=99
C
      return
      end
C
C  **********************************
C  ***** PLOTTING SUBROUTINES *****
C  ***** (multi-function plot)*****
C  **********************************
      Subroutine MGRAPH(X,Y,Z,XORG,YORG,DISOPT)
C
      implicit REAL*4 (A-Z)
      COMMON BEGTIM,FINTIM,NPTS,IOPORT,MODEL,XLEN,YLEN,PLEN,PLEN1,
     +       XTITLE,YTITLE,PTITLE,PTIT1
      real*4 X(1010),Y(1010),Z(1010)
      integer*2 NPTS,IOPORT,MODEL,XLEN,YLEN,NCHAR,NCHAR1
      character*1 DISOPT,ANS
      character*25 XTITLE,YTITLE
      character*51 PTITLE,PTIT1
C
C ... Make a new title...
    5 call CLRSCR
      if ((DISOPT .eq. 'P') .or. (DISOPT .eq. 'p')) then
         call GOTOXY(8,30)
         write(*,*) 'Current Title is:'
         call GOTOXY(10,20)
```

```
          write(*,*) PTITLE
          call GOTOXY(11,20)
          write(*,*) PTIT1
          call GOTOXY(15,25)
          write(*,'(A\)') 'Do you want to change the title? '
          read(*,'(A)') ANS
          call CLRSCR
         if ((ANS .eq. 'Y') .or. (ANS .eq. 'y')) then
             call GOTOXY(5,10)
          write(*,*) 'Enter titles in left justified format'
             call GOTOXY(12,10)
          write(*,*) '12345678901234567890123456789012345678901234567890'
             call GOTOXY(13,10)
          write(*,*) '         1         2         3         4         5'
             call GOTOXY(15,25)
          write(*,*) '# of characters -->'
             call GOTOXY(20,10)
          write(*,*) '12345678901234567890123456789012345678901234567890'
             call GOTOXY(21,10)
          write(*,*) '         1         2         3         4         5'
             call GOTOXY(23,25)
          write(*,*) '# of characters -->'
             call GOTOXY(11,11)
          read(*,'(A51)') PTITLE
             call GOTOXY(15,46)
          read(*,*) PLEN
             call GOTOXY(19,11)
          read(*,'(A51)') PTIT1
             call GOTOXY(23,46)
          read(*,*) PLEN1
         elseif ((ANS .eq. 'N') .or. (ANS .eq. 'n')) then
             go to 10
         endif
          go to 5
       endif
C
    10 call GOTOXY(10,25)
       write(*,*) 'Calculating Plotting Data'
C
       ASPRAT=.65
       CHARHT=.22
       CHARH1=.20
       PTX=0.5+(6.-PLEN*ASPRAT*CHARHT)/2.
       PTY=4.5
       PTX1=0.5+(6.-PLEN1*ASPRAT*CHARH1)/2.
       PTY1=4.1
       NCHAR=ifix(PLEN)
       NCHAR1=ifix(PLEN1)
C
       call PLOTS(0,IOPORT,MODEL)
       call FACTOR(1.00)
```

```
      call ASPECT(ASPRAT)
C ... Draw a Border
      if ((DISOPT .eq. 'P') .or. (DISOPT .eq. 'p')) then
         call PLOT(XORG,YORG,-13)
          call PLOT(8.0,0.0,2)
          call PLOT(8.0,6.0,2)
          call PLOT(0.0,6.0,2)
          call PLOT(0.0,0.0,2)
         call PLOT(1.25,1.,-13)
      elseif ((DISOPT .eq. 'M') .or. (DISOPT .eq. 'm')) then
         call PLOT(1.,1.,-13)
      endif
C
C
C  ... This scaling applies when the X axis represents Time...
      X(NPTS+1)=BEGTIM
      FIRSTX = X(NPTS+1)
      X(NPTS+2)=(X(NPTS)-X(NPTS+1))/6.
      DELTAX = X(NPTS+2)
C
      call SCALE(Y,4.,NPTS,1)
      call SCALE(Z,4.,NPTS,1)
      if (Z(NPTS+2) .gt. Y(NPTS+2)) then
         Y(NPTS+2)=Z(NPTS+2)
      else
         Z(NPTS+2)=Y(NPTS+2)
      endif
      FIRSTY = Y(NPTS+1)
      DELTAY = Y(NPTS+2)
C
      call STAXIS(.15,.22,.12,.080,3)
      call AXIS(0.0,0.0,XTITLE,XLEN,6.,0.,FIRSTX,DELTAX)
      call STAXIS(.15,.22,.12,.080,2)
      call AXIS(0.,0.,YTITLE,YLEN,4.,90.,FIRSTY,DELTAY)
      call SYMBOL(PTX,PTY,CHARHT,PTITLE,0.,NCHAR)
      call SYMBOL(PTX1,PTY1,CHARH1,PTIT1,0.,NCHAR1)
      call LINE(X,Y,NPTS,1,0,0)
      call CURVE(X,Z,NPTS,-.1)
      call PLOT(0.,0.,999)
C
      MODEL=99
      IOPORT=99
C
      return
      end
C
C    ********************************************
C    ***** PULSE WIDTH MODULATOR MODULE *****
C    ********************************************
C
      Subroutine PWMOD(TIME,NUMIT,TSTART,PERIOD,TOGGLE,POSERR,
     +    DBAND,VIN,VREF,THRESH,KPWM)
C
      IMPLICIT REAL*4 (A-Z)
      INTEGER*2 NUMIT,DIR
      LOGICAL*2 WAITNG,TOGGLE
C
C ... Reset the saw-tooth reference signal ...
        if (TIME .ge. TSTART+PERIOD) then
          TSTART=TSTART+PERIOD
          TOGGLE=.true.
        endif
C
        if (POSERR .gt. (0.+DBAND)) then
          DIR=1
          ERROR=abs(KPWM*(POSERR-DBAND))
        elseif (POSERR .lt. (0.-DBAND)) then
          DIR=-1
          ERROR=abs(KPWM*(POSERR+DBAND))
        else
          ERROR=0.
        endif
        call LIMIT(0.,1.,ERROR,ERROR)
        call RAMP(TIME,TSTART,NREF)
        VREF=NREF/PERIOD
        THRESH=1.-ERROR
C
C  ... "WAITING" is a logical variable indicating whether or not a new
C       pulse may be generated ...
        if (NUMIT .eq. 1) WAITNG=TOGGLE
C
        if (WAITNG) then
          if (VREF .gt. THRESH) then
            if (DIR .eq. 1) then
              VIN=150.
              TOGGLE=.false.
            elseif (DIR .eq. -1) then
              VIN=-150.
              TOGGLE=.false.
            endif
          elseif (VREF .lt. THRESH) then
            VIN=0.
            TOGGLE=.true.
          endif
        endif
C
       return
       end
C
C    *************************
C    ***** RELAY MODULE *****
C    *************************
```

```
C
      Subroutine RELAY(POSERR,DBAND,VIN)
C
      implicit REAL*4 (A-Z)
C
         if (POSERR .gt. DBAND) then
            VIN=150.
         elseif (POSERR .lt. -DBAND) then
            VIN=-150.
         elseif (abs(POSERR) .le. DBAND) then
            VIN=0.
         endif
C
      return
      end
C
C    ******************************************
C    ***** SATURATING AMPLIFIER MODULE *****
C    ******************************************
C
      Subroutine AMPLIF(POSERR,DBAND,KA,VIN)
C
      implicit REAL*4 (A-Z)
C
         if (abs(POSERR) .le. DBAND) then
            VIN=0.
         elseif (((POSERR-DBAND)*KA .gt. 0.) .and.
     +           ((POSERR-DBAND)*KA .lt. 1.)) then
            VIN=150.*(POSERR-DBAND)*KA
         elseif (((POSERR+DBAND)*KA .lt. 0.) .and.
     +           ((POSERR+DBAND)*KA .gt. -1.)) then
            VIN=150.*(POSERR+DBAND)*KA
         elseif ((POSERR-DBAND)*KA .ge. 1.) then
            VIN=150.
         elseif ((POSERR+DBAND)*KA .le. -1.) then
            VIN=-150.
         endif
C
      return
      end
C
C    ****************************************************
C    ***** Cutoff-Saturation Limiting Subroutine *****
C    ****************************************************
          Subroutine LIMIT(RSAT,RCUT,INPUT,OUT)
            implicit REAL*4 (A-Z)
            if (INPUT .le. RSAT) then
              OUT=RSAT
            elseif (INPUT .ge. RCUT) then
              OUT=RCUT
            else
```

```
              OUT=INPUT
            end if
C
          return
          end
C     ****************************************
C     ***** Function Switch Subroutine *****
C     ****************************************
         Subroutine FCNSW(X1,X2,X3,X4,OUT)
          implicit REAL*4 (A-Z)
          if (X1 .lt. 0.0) then
            OUT=X2
          elseif (X1 .eq. 0.0) then
            OUT=X3
          else
            OUT=X4
          end if
C
         return
         end
C     **************************************
C     ***** Step function Subroutine *****
C     **************************************
         Subroutine STEP(TIME,TSTEP,OUT)
          implicit REAL*4 (A-Z)
          if (TIME .ge. TSTEP) then
            OUT=1.0
          else
            OUT=0.0
          end if
C
         return
         end
C     *********************************
C     ***** Deadspace Subroutine *****
C     *********************************
         Subroutine DEADSP(P1,P2,VSGDEL,VSGERR)
          implicit REAL*4 (A-Z)
          if (VSGDEL .gt. P2) then
            VSGERR=VSGDEL-P2
          elseif (VSGDEL .lt. P1) then
            VSGERR=VSGDEL-P1
          else
            VSGERR=0.0
          end if
C
         return
         end
C     ****************************
C     ***** Ramp Subroutine *****
C     ****************************
```

```
        Subroutine RAMP(TIME,TRAMP,OUT)
          implicit REAL*4 (A-Z)
          if (TIME .ge. TRAMP) then
            OUT=TIME-TRAMP
          else
            OUT=0.0
          end if
C
        return
        end
C      **********************
C      *** TIME CONSTANT ***
C      **********************
C
      Subroutine TCONST(Y0,X,TAU,NTIME,NTIM,DELTIM,Y)
        implicit real*4 (A-Z)
        integer*2 NTIME,NTIM
        if (NTIME .ne. NTIM) Y0=Y
        DECAY=exp(-DELTIM/TAU)
        Y=Y0+(X-Y0)*(1.-DECAY)
        if (NTIME .eq. 1) Y=Y0
        NTIM=NTIME
C
      return
      end
C     ***********************************************
C     ***** First Order Derivative Subroutine *****
C     ***********************************************
        Subroutine DERIV(DELTIM,NTIME,NTIM1,IC2,XM1,NOWVAL,XX,XDM1,
     +                   XD,XDDM1,XDD,SLOPE)
          implicit REAL*4 (A-Z)
          integer*2 NTIME,NTIM1
C
          if (NTIME .eq. NTIM1) then
            XX=NOWVAL
          else
            XM1=XX
            XX=NOWVAL
            XDM1=XD
            XDDM1=XDD
          end if
C
          XD=(XX-XM1)/DELTIM
          if (abs(XD) .lt. 1.E-8) XD=0.
          if (NTIME .eq. 1) XD=IC2
          XDD=(XD-XDM1)/DELTIM
          if (abs(XDD) .lt. 1.E-8) XDD=0.0
C
          NTIM1=NTIME
C
          XPRED=XX+XD*DELTIM+XDD*(DELTIM**2)/2.0
          if (abs(XPRED) .lt. 1.E-8) XPRED=0.0
          SLOPE=(XPRED-XM1)/(2.0*DELTIM)
          if (abs(SLOPE) .lt. 1.E-8) SLOPE=0.0
C
        return
        end
C    ***********************************************
C    ***** Trapezoidal Integration Subroutine *****
C    ***********************************************
        Subroutine INTGRL(NTIME,NTIM2,DELTIM,IC3,PREVAL,NOWVAL,
     +                  CURVAL,OUTOLD,OUTNEW)
          implicit REAL*4 (A-Z)
          integer*2 NTIME,NTIM2
C
          if ((NTIME .eq. NTIM2) .or. (NTIME .eq. 1)) then
            CURVAL=NOWVAL
          else
            PREVAL = CURVAL
            CURVAL = NOWVAL
            OUTOLD = OUTNEW
          end if
          if (NTIME .eq. 1) OUTOLD=IC3
          OUTNEW  = OUTOLD+(CURVAL+PREVAL)*DELTIM/2.
          NTIM2=NTIME
C
        return
        end
C    *****************************************
C    ***** CLEAR SCREEN AND HOME CURSOR *****
C    *****************************************
       subroutine CLRSCR
       character*1 C1,C2,C3,C4
       integer*2 IC(4)
       equivalence (C1,IC(1)),(C2,IC(2)),(C3,IC(3)),(C4,IC(4))
       data IC/16#1B,16#5B,16#32,16#4A/
C
C *** Write Escape Code to Display ***
       write(*,1) C1,C2,C3,C4
     1 format(1X,4A1)
C
       return
       end
C    ******************************************
C    ***** Position Cursor by Row,Column *****
C    ******************************************
       subroutine GOTOXY(ROW,COLUMN)
       integer*2 IC(4),ROW,COLUMN,L
       character*1 C1,C2,C5,C8,LC(5)
       character*5 CBUFF
       equivalence (C1,IC(1)),(C2,IC(2)),(C5,IC(3)),(C8,IC(4)),
     +            (CBUFF,LC(1))
```

```
      data IC/16#1B,16#5B,16#3B,16#66/
C
      L=10000+100*ROW+COLUMN
C
C *** Write Escape Codes to a Character Buffer ***
      write(CBUFF,2) L
    2 format(I5)
C
C *** Write Escape Codes to Display ***
      write(*,3) C1,C2,LC(2),LC(3),C5,LC(4),LC(5),C8
    3 format(1X,8A1,\)
      return
      end
```

APPENDIX D

PHASE PLANE ANALYSIS PROGRAM

```
$NOfloatcalls
$NOdebug
C
C      ______________________________________________
C     |                                              |
C     |  ROSSITTO, VS   THESIS    PROF GERBA  03/25/87 |
C     |_________PHASE_PLANE_DESIGN_MODEL_____________|
C
C      This program computes and plots the characteristic slope markers
C      for the reduced order Brushless DC Motor model.  Motor parameters
C      are provided by the user. Additionally, the Non-Linear Element
C      performance is plotted. Step and Ramp responses may be analyzed.
C      Plotting density is selectable (1000pts/plt max).
C
      IMPLICIT REAL*4 (A-Z)
      COMMON XTIME,Y1,Y2,Y3,Y4,BEGTIM,FINTIM,NPTS,IOPORT,MODEL,
     +       XLEN,YLEN,PLEN,PPLANE,XTITLE,YTITLE,PTITLE
      REAL*4 X(1010),Y(1010),Y1(1010),Y2(1010),Y3(1010),Y4(1010),
     +       XTIME(1010)
      INTEGER*2 NTERMS,IOPORT,MODEL,XLEN,YLEN,NTIME,NUMIT,NTIM1,
     +          NTIM2,NTIM3,NTIM4,DIR,PMODEL,NPTS,NCTR,PPLANE,PTSPL1,
     +          SIM2PL,ECTR,EDCTR,NUMBER,NDIM,CTR,ELEMNT,PTSPLT,VCTR
      LOGICAL*2 WAITNG,TOGGLE
      CHARACTER*1 DISOPT,PLOPT
      CHARACTER*6 ANS1,ANS11,ANS21,ANS27,PRTSEL,NONLIN
      CHARACTER*25 XTITLE,YTITLE
      CHARACTER*25 NLCHAR
      CHARACTER*51 PRTCHR,PTITLE
C
C ... Introductory Page (1 time good deal!)
      call CLRSCR
      write(*,4)
      PAUSE
C     ******************************************
C     *** OPEN/READ/CLOSE INPUT DATA FILE ***
C     ******************************************
C
 13   open(7,FILE='PHPLANE.INP',STATUS='OLD',ACCESS='SEQUENTIAL')
      read(7,1000) PMODEL,PRTCHR
      read(7,1020) BEGTIM,FINTIM,MAXITS,SIM2PL
      read(7,1022) KPWM,KV,E0,EDOT0
      read(7,1024) R,L,J,F,KT,KB,KP
      read(7,1026) RSLOPE,PERIOD,DBAND
      read(7,1028) KA,PTSPLT,XORG,YORG,WFACT
      read(7,1030) EMIN,EMAX,EDMIN,EDMAX
      close(7,STATUS='KEEP')
```

```
C     ****************************************
C     *** DISPLAY MAIN MENU SELECTIONS ***
C     ****************************************
C
   1  call CLRSCR
      call GOTOXY(8,1)
      write(*,5)
      read(*,'(A)') ANS1
C  ... Hardware Options ...
      if ((ANS1 .eq. 'h') .or. (ANS1 .eq. 'H')) then
C
 101     call CLRSCR
         call GOTOXY(17,24)
         write(*,*)'*** CURRENT PRINTER SELECTION ***'
         call GOTOXY(20,20)
         write(*,*) PRTCHR
         call GOTOXY(10,1)
         write(*,105)
         read(*,'(A)') ANS11
C
C  ... Printer Options ...
         if ((ANS11 .eq. 'p') .or. (ANS11 .eq. 'P')) then
 131        call CLRSCR
            write(*,130)
            read(*,'(A)') PRTSEL
C
            if (PRTSEL .eq. '0') then
               PRTCHR='Epson FX-80 Printer, single density'
               PMODEL=0
            elseif (PRTSEL .eq. '1') then
               PRTCHR='Epson FX-80 Printer, double density'
               PMODEL=1
            elseif (PRTSEL .eq. '2') then
               PRTCHR='Epson FX-80 Printer, dble spd,dual density'
               PMODEL=2
            elseif (PRTSEL .eq. '3') then
               PRTCHR='Epson FX-80 Printer, quad density'
               PMODEL=3
            elseif (PRTSEL .eq. '4') then
               PRTCHR='Epson FX-80 Printer, CRT Graphics I'
               PMODEL=4
            elseif (PRTSEL .eq. '5') then
               PRTCHR='Epson FX-80 Printer, plotter graphics'
               PMODEL=5
            elseif (PRTSEL .eq. '6') then
               PRTCHR='Epson FX-80 Printer, CRT Graphics II'
               PMODEL=6
            elseif (PRTSEL .eq. '10') then
               PRTCHR='Epson FX-100 Printer, single density'
               PMODEL=7
            elseif (PRTSEL .eq. '11') then
```

```
              PRTCHR='Epson FX-100 Printer, double density'
              PMODEL=11
           elseif (PRTSEL .eq. '12') then
              PRTCHR='Epson FX-100 Printer, dble spd,dual density'
              PMODEL=12
           elseif (PRTSEL .eq. '13') then
              PRTCHR='Epson FX-100 Printer, quad density'
              PMODEL=13
           elseif (PRTSEL .eq. '14') then
              PRTCHR='Epson FX-100 Printer, CRT Graphics I'
              PMODEL=14
           elseif (PRTSEL .eq. '15') then
              PRTCHR='Epson FX-100 Printer, plotter graphics'
              PMODEL=15
           elseif (PRTSEL .eq. '16') then
              PRTCHR='Epson FX-100 Printer, CRT Graphics II'
              PMODEL=16
           elseif (PRTSEL .eq. '20') then
              PRTCHR='HP 7470A Graphics Plotter'
              PMODEL=20
           elseif (PRTSEL .eq. '30') then
              PRTCHR='HP 7475A Graphics Plotter'
              PMODEL=30
           elseif (PRTSEL .eq. '60') then
              PRTCHR='HP 2686A Laser Jet Printer'
              PMODEL=60
C
C  ... Quit the Printer Menu ...
           elseif ((PRTSEL .eq. 'Q') .or. (PRTSEL .eq. 'q')) then
              go to 101
           else
              go to 131
           endif
           go to 101
C
C  ... Quit the Hardware Menu ...
        elseif((ANS11 .eq. 'q') .or. (ANS11 .eq. 'Q')) then
           go to 1
        else
           go to 101
        endif
C
C  ... Motor Parameters ...
     elseif ((ANS1 .eq. 'm') .or. (ANS1 .eq. 'M')) then
C
 201    call CLRSCR
        write(*,230) KT,KB,R,L,J,F,KP,KV
        read(*,'(A)') ANS21
C
        if (ANS21 .eq. 'KT') then
           call GOTOXY(24,1)
```

```
            write(*,'(A\)')'Enter a REAL value for KT--> '
            read(*,*) KT
            go to 201
         elseif (ANS21 .eq. 'KB') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for KB--> '
            read(*,*) KB
            go to 201
         elseif (ANS21 .eq. 'R') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for R--> '
            read(*,*) R
            go to 201
         elseif (ANS21 .eq. 'L') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for L--> '
            read(*,*) L
            go to 201
         elseif (ANS21 .eq. 'J') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for J--> '
            read(*,*) J
            go to 201
         elseif (ANS21 .eq. 'F') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for F--> '
            read(*,*) F
            go to 201
         elseif (ANS21 .eq. 'KP') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for KP--> '
            read(*,*) KP
            go to 201
         elseif (ANS21 .eq. 'KV') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for KV--> '
            read(*,*) KV
            go to 201
C  ... Quit Motor Parameters Menu ...
         elseif (ANS21 .eq. 'Q') then
            go to 1
         else
            go to 201
         end if
C
C  ... NON-LINEAR ELEMENT SELECTION MENU ...
C
      elseif ((ANS1 .eq. 'n') .or. (ANS1 .eq. 'N')) then
   14    call CLRSCR
         call GOTOXY(21,1)
         write(*,272) NLCHAR
      call GOTOXY(1,1)
      write(*,270)
      read(*,'(A)') ANS27
C ... RELAY AS NON-LINEAR ELEMENT ...
      if ((ANS27 .eq. 'r') .or. (ANS27 .eq. 'R')) then
        ELEMNT=1
        NLCHAR='RELAY'
 291    call CLRSCR
        NONLIN='R'
        write(*,290) DBAND
        read(*,'(A)') ANS21
C
          if (ANS21 .eq. 'DBAND') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for DBAND--> '
            read(*,*) DBAND
            go to 291
          elseif ((ANS21 .eq. 'q') .or. (ANS21 .eq. 'Q')) then
            go to 14
          else
            go to 291
          endif
C ... PULSE WIDTH MODULATOR AS NON-LINEAR ELEMENT ...
      elseif ((ANS27 .eq. 'p') .or. (ANS27 .eq. 'P')) then
        ELEMNT=3
        NLCHAR='PULSE WIDTH MODULATOR'
 301    call CLRSCR
        NONLIN='P'
        write(*,300) DBAND,PERIOD,KPWM
        read(*,'(A)') ANS21
C
          if (ANS21 .eq. 'DBAND') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for DBAND--> '
            read(*,*) DBAND
            go to 301
          elseif (ANS21 .eq. 'PERIOD') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for PERIOD--> '
            read(*,*) PERIOD
            go to 301
          elseif (ANS21 .eq. 'KPWM') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for KPWM--> '
            read(*,*) KPWM
            go to 301
          elseif ((ANS21 .eq. 'q') .or. (ANS21 .eq. 'Q')) then
            go to 14
          else
            go to 301
          endif
```

```
C
C  ... SATURATING AMPLIFIER AS NON-LINEAR ELEMENT ...
         elseif ((ANS27 .eq. 'a') .or. (ANS27 .eq. 'A')) then
            ELEMNT=2
            NLCHAR='SATURATING AMPLIFIER'
  281       call CLRSCR
            NONLIN='A'
            write(*,280) DBAND,KA
            read(*,'(A)') ANS21
C
           if (ANS21 .eq. 'DBAND') then
              call GOTOXY(24,1)
              write(*,'(A\)')'Enter a REAL value for DBAND--> '
              read(*,*) DBAND
              go to 281
           elseif (ANS21 .eq. 'KA') then
              call GOTOXY(24,1)
              write(*,'(A\)')'Enter a REAL value for KA--> '
              read(*,*) KA
              go to 281
           elseif ((ANS21 .eq. 'q') .or. (ANS21 .eq. 'Q')) then
              go to 14
           else
              go to 281
           endif
C
         elseif ((ANS27 .eq. 'n') .or. (ANS27 .eq. 'N')) then
             go to 400
         elseif ((ANS27 .eq. 'q') .or. (ANS27 .eq. 'Q')) then
             go to 1
         else
             go to 14
         endif
C
C  ... Phase Plane Design Menu ...
      elseif ((ANS1 .eq. 'p') .or. (ANS1 .eq. 'P')) then
C
 204     call CLRSCR
         write(*,260) EMIN,EMAX,EDMIN,EDMAX
         read(*,'(A)') ANS21
C
         if (ANS21 .eq. 'EMIN') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter the minimum value of E--> '
            read(*,*) EMIN
            go to 204
         elseif (ANS21 .eq. 'EMAX') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter the maximum value of E--> '
            read(*,*) EMAX
            go to 204
```

```
          elseif (ANS21 .eq. 'EDMIN') then
             call GOTOXY(24,1)
             write(*,'(A\)')'Enter the minimum value of E DOT--> '
             read(*,*) EDMIN
             go to 204
          elseif (ANS21 .eq. 'EDMAX') then
             call GOTOXY(24,1)
             write(*,'(A\)')'Enter the maximum value of E DOT--> '
             read(*,*) EDMAX
             go to 204
C  ... Quit PHASE PLANE Dimensioning Menu ...
          elseif ((ANS21 .eq. 'q') .or. (ANS21 .eq. 'Q')) then
             go to 1
          else
             go to 204
          end if
C
C  ... Simulation Options ...
        elseif ((ANS1 .eq. 'o') .or. (ANS1 .eq. 'O')) then
C
 202      call CLRSCR
C
          DELTIM=(FINTIM-BEGTIM)/(float(PTSPLT)*SIM2PL)
          if (FINTIM/DELTIM .gt. MAXITS) DELTIM =FINTIM/MAXITS
          NTERMS=IFIX(FINTIM/DELTIM)+1
C
          write(*,240) BEGTIM,FINTIM,MAXITS,SIM2PL,PTSPLT,E0,EDOT0,
     +                 RSLOPE,XORG,YORG,WFACT,DELTIM,NTERMS
          read(*,'(A)') ANS21
C
          if (ANS21 .eq. 'BEGTIM') then
             call GOTOXY(24,1)
             write(*,'(A\)')'Enter a REAL value for BEGTIM--> '
             read(*,*) BEGTIM
             go to 202
          elseif (ANS21 .eq. 'FINTIM') then
             call GOTOXY(24,1)
             write(*,'(A\)')'Enter a REAL value for FINTIM--> '
             read(*,*) FINTIM
             go to 202
          elseif (ANS21 .eq. 'MAXITS') then
             call GOTOXY(24,1)
             write(*,'(A\)')'Enter a REAL value for MAXITS--> '
             read(*,*) MAXITS
             go to 202
          elseif (ANS21 .eq. 'SIM2PL') then
             call GOTOXY(24,1)
             write(*,'(A\)')'Enter a INTEGER value for SIM2PL--> '
             read(*,*) SIM2PL
             go to 202
          elseif (ANS21 .eq. 'PTSPLT') then
```

```
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a INTEGER value for PTSPLT--> '
            read(*,*) PTSPL1
            if (PTSPL1 .gt. 1000) then
               PTSPLT=1000
            else
               PTSPLT=PTSPL1
            endif
            go to 202
         elseif (ANS21 .eq. 'E0') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for E0 (degrees)--> '
            read(*,*) E0
            go to 202
         elseif (ANS21 .eq. 'EDOT0') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for EDOT0 (deg/sec)--> '
            read(*,*) EDOT0
            go to 202
         elseif (ANS21 .eq. 'RSLOPE') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for RSLOPE (deg/sec)--> '
            read(*,*) RSLOPE
            go to 202
         elseif (ANS21 .eq. 'XORG') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for XORG--> '
            read(*,*) XORG
            go to 202
         elseif (ANS21 .eq. 'YORG') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for YORG--> '
            read(*,*) YORG
            go to 202
         elseif (ANS21 .eq. 'WFACT') then
            call GOTOXY(24,1)
            write(*,'(A\)')'Enter a REAL value for WFACT--> '
            read(*,*) WFACT
            go to 202
C  ... Quit Simulation Options Menu ...
         elseif (ANS21 .eq. 'Q') then
            go to 1
         else
            go to 202
         end if
C  ... Save Options to File ...
      elseif ((ANS1 .eq. 's') .or. (ANS1 .eq. 'S')) then
C
C     ******************************************
C     *** OPEN/WRITE/CLOSE INPUT DATA FILE ***
C     ******************************************
```

```
C
          open(7,FILE='PHPLANE.INP',STATUS='NEW')
          write(7,1000) PMODEL,PRTCHR
          write(7,1020) BEGTIM,FINTIM,MAXITS,SIM2PL
          write(7,1022) KPWM,KV,E0,EDOT0
          write(7,1024) R,L,J,F,KT,KB,KP
          write(7,1026) RSLOPE,PERIOD,DBAND
          write(7,1028) KA,PTSPLT,XORG,YORG,WFACT
          write(7,1030) EMIN,EMAX,EDMIN,EDMAX
          write(7,2000)
          close(7,STATUS='KEEP')
C
          go to 1
C
C  ... Run the Program ...
      elseif ((ANS1 .eq. 'r') .or. (ANS1 .eq. 'R')) then
         go to 2
C
C  ... Quit the Program ...
      elseif ((ANS1 .eq. 'q') .or. (ANS1 .eq. 'Q')) then
          stop
      else
          go to 1
      endif
C
C  ... Open an Output Data File ...
    2 open(4,file='PHPLANE.OUT',status='NEW')
C
      PI=3.14159
      N=.1
C
C  ... Initializations ...
      NCTR=0
      NPTS=0
      NTIM2=1
      NTIM3=0
      NTIM4=0
      PARG1=0.0
      PARG2=0.0
      PVAL4=0.
      CARG1=0.0
      CARG2=0.0
      CVAL4=0.
      TOT1=0.0
      TOT2=0.0
      TVAL1=0.0
      TVAL2=0.0
      TVAL4=0.
      XM1=0.0
      XX=0.0
      XDM1=0.0
      XD=0.0
      XDDM1=0.0
      XDD=0.0
      X1=0.0
      F1=0.0
      F2=0.0
      X3=0.0
      WM1=0.0
      WM=0.0
      IM=0.
      IM0=0.
      TSTART=0.0
      THEDEG=0.0
      TOGGLE=.true.
      PPLANE=0
      NUMBER=0
      NDIM=20
C
C  ... Preliminary Relationships ...
C  ... Initial perturbation of THETA for stability check. (0 otherwise)
      E0RAD=-E0*PI/(180.*N)
      EDOT0R=-EDOT0*PI/(180.*N)
      if (KP .ne. 0.) WM0=EDOT0R/KP
      X2=WM0
      if (KP .ne. 0.) THETA0=E0RAD/KP
      PTHETA=THETA0
      TAU1=L/R
      TAU2=J/F
C
      call CLRSCR
C ... Display the simulation header ...
      call CLRSCR
      call GOTOXY(10,29)
      write(*,*) 'Simulation in Progress'
      DELTIM=(FINTIM-BEGTIM)/(float(PTSPLT)*SIM2PL)
      if (FINTIM/DELTIM .gt. MAXITS) DELTIM =FINTIM/MAXITS
      NTERMS=IFIX(FINTIM/DELTIM)+1
C  ... Output Simulation Options to Output Data File ...
      write(4,1200) BEGTIM,FINTIM,MAXITS,SIM2PL,DELTIM,KT,KB,R,L,J,F,
     +              KP,KV,KPWM,KA,RSLOPE
      write(4,1201) PERIOD,DBAND,E0,EDOT0
C
      call GOTOXY(14,1)
      write(*,15) DELTIM,NTERMS
   15 format(16X,'Simulation Step Size --> ',F9.8,' seconds',/,
     +       17X,'Total Number of Steps--> ',I6)
      call GOTOXY(21,1)
C
      if ((NONLIN .eq. 'r') .or. (NONLIN .eq. 'R')) then
       write(*,*) '                   *** NON-LINEAR ELEMENT IS RELAY ***'
      elseif ((NONLIN .eq. 'a') .or. (NONLIN .eq. 'A')) then
```

```
        write(*,*) '           *** NON-LINEAR ELEMENT IS SATURATING AMPLI
     +FIER ***'
       elseif ((NONLIN .eq. 'p') .or. (NONLIN .eq. 'P')) then
        write(*,*) '                   *** NON-LINEAR ELEMENT IS PWM ***'
       else
        write(*,*) '             *** NON-LINEAR ELEMENT NOT SELECTED ***'
        write(*,*) '                   ... Return to Main Menu ...'
        PAUSE
        go to 1
       endif
C
      SPACE=DELTIM/2.0
C
C     ***********************************
C     *** START MAIN SIMULATION LOOP ***
C     ***********************************
C
      DO 100 NTIME=1,NTERMS
        TIME=(NTIME-1)*DELTIM
        NUMIT=0
        THETA=PTHETA
C
C     ************************************
C     *** START INNER SIMULATION LOOP ***
C     ************************************
C
 200    NUMIT=NUMIT+1
        WM=X2
C
        THETAF=.1*THETA*180./PI
        OMEGAF=.1*WM*180./PI
        ORDER=RSLOPE*TIME
        POSERR=ORDER-KP*THETAF-KV*OMEGAF
C
C  ... Utilization of Non-Linear Element ...
C  ... PULSE WIDTH MODULATOR ...
      if ((NONLIN .eq. 'p') .or. (NONLIN .eq. 'P')) then
         call PWMOD(TIME,NUMIT,TSTART,PERIOD,TOGGLE,POSERR,
     +              DBAND,AGCSAT,AGCCUT,ERRSAT,ERRCUT,VIN,VREF,THRESH,
     +              KPWM)
C  ... IDEAL RELAY ...
      elseif ((NONLIN .eq. 'r') .or. (NONLIN .eq. 'R')) then
         call RELAY(POSERR,DBAND,VIN)
C  ... SATURATING AMPLIFIER ...
      elseif ((NONLIN .eq. 'a') .or. (NONLIN .eq. 'A')) then
         call AMPLIF(POSERR,DBAND,KA,VIN)
      else
         call GOTOXY(21,1)
         write(*,*) '          *** NON-LINEAR ELEMENT NOT SELECTED ***'
         write(*,*) '                ... Return to Main Menu ...'
         PAUSE
         go to 1
      endif
C
        EN=VIN-WM*KB
C
C  ...Electrical Time Constant due to Inductance Neglected ...
C-----> call TCONST(IM0,EN/R,TAU1,NTIME,NTIM1,DELTIM,IM)
        IM=EN/R
        TM=IM*KT
        call TCONST(WM0,TM/F,TAU2,NTIME,NTIM2,DELTIM,WM1)
      call INTGRL(NTIME,NTIM4,DELTIM,THETA0,PVAL4,WM1,CVAL4,TVAL4,THET1)
      THETA=THET1
C
C     **************************************************
C     *** CONVERGENCE CRITERIA (Newton's Method) ***
C     **************************************************
C
      if (NTIME .eq. 1) then
        X3=WM1
        F2=0.
        go to 150
      end if
C
      if (NUMIT .eq. 1) then
        F2=(WM1-WM)*1.2
        X3=1.001*WM1+1.0E-4
        RELERR=abs(F2/X3)
        go to 310
      end if
C
      F2=WM1-WM
      if (F1 .eq. F2) F2=.999*F2-1.E-8
      if (X2 .ne. 0.) RELERR=abs(F2/X2)
      if (X2 .eq. 0.) RELERR=1.
      if (RELERR .gt. 1.E-8) then
         X3=X2-F2*(X1-X2)/(F1-F2)
      endif
  310 X1=X2
      X2=X3
      F1=F2
C
      WM=X2
C
      if (NUMIT .ge. 10) go to 150
      if (RELERR .gt. 1.E-8) go to 200
C
C     ***********************************
C     *** END INNER SIMULATION LOOP ***
C     ***********************************
C
  150 call DERIV(DELTIM,NTIME,NTIM3,0.,XM1,WM1,XX,XDM1,XD,XDDM1,XDD,
     +           ALPHA)
C
      X2=WM1+ALPHA*DELTIM
      PTHETA=THETA+WM1*DELTIM
      THETAF=.1*THETA*180./PI
      OMEGAF=.1*WM1*180./PI
      DIRLOG=VIN/150.
      if (ELEMNT .eq. 1) THRESH=POSERR
      if (ELEMNT .eq. 2) THRESH=POSERR
      if (ELEMNT .ne. 3) VREF=0.
C
C  ... Generate Plotting Arrays ...
      if (TIME .ge. BEGTIM) then
        NCTR=NCTR+1
        if ((mod(NCTR,SIM2PL) .eq. 0) .or. (NCTR .eq. 1)) then
          NPTS=NPTS+1
          X(NPTS)=ORDER-KP*THETAF
          Y(NPTS)=RSLOPE-KP*OMEGAF
          XTIME(NPTS)=TIME
          Y1(NPTS)=POSERR
          Y2(NPTS)=VREF
          Y3(NPTS)=THRESH
          Y4(NPTS)=DIRLOG
        endif
      endif
C
  100 CONTINUE
C
C     **********************************
C     *** END MAIN SIMULATION LOOP ***
C     **********************************
C
      close(4,status='KEEP')
C
C     ********************************
C     ***** Plotting selection *****
C     ********************************
C
C *** Clear Screen & Home Cursor ***
  400 call CLRSCR
C
      write(*,1305)
      read(*,'(A)') DISOPT
C
      if ((DISOPT .eq. 'm') .or. (DISOPT .eq. 'M')) then
        MODEL=99
        IOPORT=99
      elseif ((DISOPT .eq. 'p') .or. (DISOPT .eq. 'P')) then
        MODEL=PMODEL
        IOPORT=1
C  ... Ioport=9650 is COM2 ...
```

```
        if ((MODEL .eq. 20) .or. (MODEL .eq. 30)) IOPORT=9650
      elseif ((DISOPT .eq. 'r') .or. (DISOPT .eq. 'R')) then
        GO TO 13
      elseif ((DISOPT .eq. 's') .or. (DISOPT .eq. 'S')) then
C
C     ******************************************
C     *** OPEN/WRITE/CLOSE INPUT DATA FILE ***
C     ******************************************
C
          open(7,FILE='PHPLANE.INP',STATUS='NEW')
          write(7,1000) PMODEL,PRTCHR
          write(7,1020) BEGTIM,FINTIM,MAXITS,SIM2PL
          write(7,1022) KPWM,KV,E0,EDOTO
          write(7,1024) R,L,J,F,KT,KB,KP
          write(7,1026) RSLOPE,PERIOD,DBAND
          write(7,1028) KA,PTSPLT,XORG,YORG,WFACT
          write(7,1030) EMIN,EMAX,EDMIN,EDMAX
          write(7,2000)
          close(7,STATUS='KEEP')
C
          go to 400
C
      elseif ((DISOPT .eq. 'w') .or. (DISOPT .eq.. 'W')) then
C   ... Printer ready?? ...
          call CLRSCR
          call GOTOXY(12,25)
          write(*,*) 'Please ensure PRINTER is ready'
          call GOTOXY(20,1)
          PAUSE
C   ... Output Simulation Options to Printer ...
          open(8,file='prn',status='new')
C
          write(8,1200) BEGTIM,FINTIM,MAXITS,SIM2PL,DELTIM,
     +                  KT,KB,R,L,J,F,KP,KV,KPWM,KA,RSLOPE
          write(8,1201) PERIOD,DBAND,E0,EDOTO
          write(8,1202)
 1202 format('1')
          close(8,status='KEEP')
          go to 400
C
      elseif ((DISOPT .eq. 'Q') .or. (DISOPT .eq. 'q')) then
        GO TO 460
      else
        go to 400
      end if
C
  410 call CLRSCR
      if ((DISOPT .eq. 'p') .or. (DISOPT .eq. 'P')) then
        call GOTOXY(20,20)
        write(*,*) PRTCHR
        call GOTOXY(1,1)
      endif
      write(*,1300)
      read(*,'(A)') PLOPT
C
      if ((PLOPT .eq. 'Q') .or. (PLOPT .eq. 'q')) then
        go to 400
      elseif (PLOPT .eq. '1') then
         if (ELEMNT .eq. 2) KAPWM=KA
         if (ELEMNT .eq. 3) KAPWM=KPWM
C
         call PGRAPH(X,Y,NPTS,EMIN,EMAX,EDMIN,EDMAX,DBAND,KT,KP,
     +      KV,KB,F,R,J,ANS27,IOPORT,MODEL,KAPWM,ELEMNT,RSLOPE,
     +      XORG,YORG,WFACT,PERIOD,DISOPT,BEGTIM,FINTIM)
      elseif (PLOPT .eq. '2') then
         if (ELEMNT .eq. 2) KAPWM=KA
         if (ELEMNT .eq. 3) KAPWM=KPWM
         XTITLE='TIME (sec)'
         XLEN=-10
         if (ELEMNT .eq. 3) then
            YTITLE='PWM RESPONSE'
            YLEN=12
         elseif (ELEMNT .eq. 1) then
            YTITLE='RELAY RESPONSE'
            YLEN=15
         elseif (ELEMNT .eq. 2) then
            YTITLE='AMPLIFIER RESPONSE'
            YLEN=19
         endif
C
         if ((DISOPT .eq. 'M') .or. (DISOPT .eq. 'm')) then
            call M1GRAPH(ELEMNT)
         elseif ((DISOPT .eq. 'P') .or. (DISOPT .eq. 'p')) then
            call MGRAPH(DISOPT,KAPWM,DBAND,XORG,YORG,WFACT,ELEMNT)
         endif
      else
        go to 410
      endif
C
      go to 400
  460 continue
C
C     ******************************
C     *** I/O FORMAT STATEMENTS ***
C     ******************************
C
    4 format(////,24X,'REDUCED ORDER MODEL PHASE PLANE DESIGN',/,
     +            24X,'     LT Vincent S. Rossitto, USN',/,
     +            24X,'      Naval Postgraduate School',//,
     +            24X,'             March 1987',//////)
C
    5 format(32X,'*** MAIN MENU ***',//,
     +       20X,'[H]----> HARDWARE Configuration Menu',/,
     +       20X,'[M]----> MOTOR Parameter Menu',/,
     +       20X,'[N]----> NON-LINEAR Element Selection Menu',/,
     +       20X,'[P]----> PHASE PLANE Dimensioning Menu',/,
     +       20X,'[O]----> OPTIONS for Simulation',/,
     +       20X,'[S]----> SAVE All Changes',/,
     +       20X,'[R]----> RUN Simulation Program',/,
     +       20X,'[Q]----> QUIT the Program',//,
     +        8X,'ENTER SELECTION---->',\)
 105    format(30X,'*** HARDWARE MENU ***',//,
     +       20X,'[P]----> PRINTER/PLOTTER configuration change',/,
     +       20X,'[Q]----> QUIT THIS MENU',//,
     +        8X,'ENTER SELECTION---->',\)
 1000 format(1X,I3,2X,A50)
 1020 format(1x,2F12.7,F12.3,1X,I3)
 1022 format(1X,4F15.7)
 1024 format(1X,7F8.4)
 1026 format(1X,3F15.7)
 1028 format(1X,F12.7,I5,1X,3F12.7)
 1030 format(1X,4F12.4)
 2000 format(1X,'END OF FILE')
C
 130  FORMAT(24X,'*** PRINTER OPTIONS MENU ***',//,
     +  15X,'[0] --> Epson FX-80 Printer, single density',/,
     +  15X,'[1] --> Epson FX-80 Printer, double density',/,
     +  15X,'[2] --> Epson FX-80 Printer, dble spd,dual density',/,
     +  15X,'[3] --> Epson FX-80 Printer, quad density',/,
     +  15X,'[4] --> Epson FX-80 Printer, CRT Graphics I',/,
     +  15X,'[5] --> Epson FX-80 Printer, plotter graphics',/,
     +  15X,'[6] --> Epson FX-80 Printer, CRT Graphics II',/,
     +  15X,'[10] -> Epson FX-100 Printer, single density',/,
     +  15X,'[11] -> Epson FX-100 Printer, double density',/,
     +  15X,'[12] -> Epson FX-100 Printer, dble spd,dual density',/,
     +  15X,'[13] -> Epson FX-100 Printer, quad density',/,
     +  15X,'[14] -> Epson FX-100 Printer, CRT Graphics I',/,
     +  15X,'[15] -> Epson FX-100 Printer, plotter graphics',/,
     +  15X,'[16] -> Epson FX-100 Printer, CRT Graphics II',/,
     +  15X,'[20] -> HP 7470A Graphics Plotter',/,
     +  15X,'[30] -> HP 7475A Graphics Plotter',/,
     +  15X,'[60] -> HP 2686A Laser Jet Printer (NPS installation)',/,
     +  15X,'[Q] -->   QUIT THIS MENU',//,
     +  3X,'Enter Printer Selection Integer or Q to QUIT ---> ',\)
C
 230  format(12X,'*** MOTOR PARAMETER SETTINGS MENU ***',//,
     + 4X,F12.7,1X,'[KT]      Motor Torque Constant',/,
     + 4X,F12.7,1X,'[KB]      Motor Back EMF Constant',/,
     + 4X,F12.7,1X,'[R]       Motor Equivalent Resistance (ohms)',/,
     + 4X,F12.7,1X,'[L]       Motor Inductance (henries)',/,
     + 4X,F12.7,1X,'[J]       Motor Inertia (oz-in/s^2)',/,
     + 4X,F12.7,1X,'[F]       Motor Viscous Friction Coeff',/,
     + 4X,F12.7,1X,'[KP]      Motor Position Feedback Constant',/,
     + 4X,F12.7,1X,'[KV]     Motor Velocity Feedback Constant',/,
     + 17X,'[Q]      QUIT THIS MENU',//,
     + 1X,'Enter variable name (UPPERCASE) or Q to QUIT ---> ',\)
C
 240  format(12X,'*** SIMULATION OPTIONS MENU ***',//,
     + 1X,F15.7,1X,'[BEGTIM]  Start Time of Plotting Window',/,
     + 1X,F15.7,1X,'[FINTIM]  Stop Time of Plotting Window',/,
     + 1X,F15.4,1X,'[MAXITS]  Max Number of Simulation Iterations',/,
     + 13X,I3,1X,'[SIM2PL]  Ratio: Points Simulated/Points Plotted',/,
     + 12X,I4,1X,'[PTSPLT]  # of Points per Curve per Plot(1000max)',/,
     + 1X,F15.7,1X,'[E0]      Initial E Perturbation Offset (deg)',/,
     + 1X,F15.7,1X,'[EDOT0]   Initial EDOT Perturbation Offset(deg/s)',/,
     + 1X,F15.7,1X,'[RSLOPE] Ramp Slope (0 for Step; (+) for Ramp)',/,
     + 1X,F15.7,1X,'[XORG]    X Coordinate of Reference Origin',/,
     + 1X,F15.7,1X,'[YORG]    Y Coordinate of Reference Origin',/,
     + 1X,F15.7,1X,'[WFACT]  Plotting Scaling Factor (0.75 nominal)',/,
     + 17X,'[Q]        QUIT THIS MENU',///,
     + 15X,'Computed simulation step size ---> ',F9.8, 'seconds',/,
     + 15X,'Computed total number of steps---> ',I6,//,
     + 1X,'Enter variable name (UPPERCASE) or Q to QUIT ---> ',\)
C
 260  format(///,16X,'*** PHASE PLANE DIMENSIONING MENU ***',//,
     + 1X,F15.7,1X,'[EMIN]    Minimum E to be Plotted on Grid',/,
     + 1X,F15.7,1X,'[EMAX]    Maximum E to be Plotted on Grid',/,
     + 1X,F15.7,1X,'[EDMIN]   Minimum E DOT to be Plotted on Grid',/,
     + 1X,F15.7,1X,'[EDMAX]   Maximum E DOT to be Plotted on Grid',/,
     + 17X,'[Q]        QUIT THIS MENU',//,
     + 1X,'Enter variable name (UPPERCASE) or Q to QUIT ---> ',\)
C
 270  format(///,8X,'*** NON-LINEAR ELEMENT SELECTION ***',//,
     + 10X,'[R]    Relay (Bang-Bang)',/,
     + 10X,'[P]    Pulse Width Modulator',/,
     + 10X,'[A]    Amplifier (Saturating)',/,
     + 10X,'[N]    No Trajectory Calculation/ Only Phase PLANE Map',/,
     + 10X,'[Q]    QUIT THIS MENU/RETURN TO MAIN MENU',//,
     + 1X,'Enter Selection ---> ',\)
C
 272  format(10X,'CURRENT SELECTION --> ',A30)
C
 280  format(///,8X,'*** SATURATING AMPLIFIER SPECIFICATIONS ***',//,
     + 1X,F15.7,1X,'[DBAND]   Deadband Applied to System Feedback',/,
     + 1X,F15.7,1X,'[KA]      Amplifier Gain',/,
     + 17X,'[Q]        QUIT THIS MENU',//,
     + 1X,'Enter the selection (UPPERCASE) ---> ',\)
C
 290  format(///,15X,'*** RELAY SPECIFICATIONS ***',//,
     + 1X,F15.7,1X,'[DBAND]   Deadband Applied to System Feedback',/,
     + 17X,'[Q]        QUIT THIS MENU',//,
     + 1X,'Enter the selection (UPPERCASE) ---> ',\)
C
 300  format(///,5X,'*** PULSE WIDTH MODULATOR SPECIFICATIONS ***',//,
     + 1X,F15.7,1X,'[DBAND]   Deadband Applied to System Feedback',/,
     + 1X,F15.7,1X,'[PERIOD]  Period of PWM Reference Cycle(sec)',/,
     + 1X,F15.7,1X,'[KPWM]    PWM Amplifier Gain',/,
     + 17X,'[Q]        QUIT THIS MENU',//,
     + 1X,'Enter the selection (UPPERCASE) ---> ',\)
C
 1200 format(20X,'LINEAR MODEL OF BRUSHLESS DC MOTOR',//,
     + 1X,F15.7,1X,'[BEGTIM]  Start Time of Plotting Window',/,
     + 1X,F15.7,1X,'[FINTIM]  Stop Time of Plotting Window',/,
     + 1X,F15.4,1X,'[MAXITS]  Max Number of Simulation Iterations',/,
     + 13X,I3,1X,'[SIM2PL]  Ratio: Points Simulated/Plotted',/,
     + 1X,F15.9,1X,'[DELTIM]  Simulation Step Size',/,
     + 1X,F15.7,1X,'[KT]      Motor Torque Constant',/,
     + 1X,F15.7,1X,'[KB]      Motor Back EMF Constant',/,
     + 1X,F15.7,1X,'[R]       Motor Equivalent Resistance (ohms)',/,
     + 1X,F15.7,1X,'[L]       Motor Inductance (henries)',/,
     + 1X,F15.7,1X,'[J]       Motor Inertia (oz-in/s^2)',/,
     + 1X,F15.7,1X,'[F]       Motor Viscous Friction Coeff',/,
     + 1X,F15.7,1X,'[KP]      Motor Position Feedback Constant',/,
     + 1X,F15.7,1X,'[KV]      Motor Velocity Feedback Constant',/,
     + 1X,F15.7,1X,'[KPWM]    PWM Amplifier Gain',/,
     + 1X,F15.7,1X,'[KA]      Saturating Amplifier Gain (if used)',/,
     + 1X,F15.7,1X,'[RSLOPE]  Ramp Slope (0 for Step; (+) for Ramp)')
 1201 format(1X,F15.7,1X,'[PERIOD]  Period of PWM Reference Cycle',/,
     + 1X,F15.7,1X,'[DBAND]   Position Feedback Deadband',/,
     + 1X,F15.7,1X,'[E0]      Initial E Perturbation Offset (deg)',/,
     + 1X,F15.7,1X,'[EDOT0]   Initial EDOT Perturbation Offset (deg/s)')
C
 1205 FORMAT(1X,F8.6,1X,1P5E12.3)
 1300 FORMAT(/////,2X,'The following are plotting options',//,
     +           5X,'[1] PHASE PLANE Trajectory',/,
     +           5X,'[2] NON-LINEAR Element Performance (PRINT only)',/,
     +           5X,'[Q] QUIT THIS MENU',//,
     +           2X,'Enter selection [1,2,Q] ---> ',\)
C
 1305 FORMAT(/////,2X,'Display options:',/,
     +           5X,'[M] MONITOR',/,
     +           5X,'[P] PRINTER',/,
     +           5X,'[R] RETURN TO START-UP MENU (RE-INITIALIZE)',/,
     +           5X,'[S] SAVE SIMULATION SPECIFICATIONS TO DISK',/,
     +           5X,'[W] WRITE SIMULATION SPECIFICATIONS TO PRINTER',/,
     +           5X,'[Q] QUIT THE PROGRAM',//,
     +           2X,'Enter selection [M,P,R,S,W,Q] ---> ',\)
C
 1500 format(1X,I3,2X,A50)
C
      STOP
      END
C -----------------------------------------------------------------
C  **********************************
C  ***** PLOTTING SUBROUTINES *****
```

```
C  *****( phase- plane   plot)*****
C  *********************************
      Subroutine PGRAPH(X,Y,NPTS,EMIN,EMAX,EDMIN,EDMAX,DBAND,
     +    KT,KP,KV,KB,F,R,J,ANS27,IOPORT,MODEL,KA,ELEMNT,RSLOPE,
     +    XORG,YORG,WFACT,PERIOD,DISOPT,BEGTIM,FINTIM)
C
      implicit REAL*4 (A-Z)
      real*4 X(1010),Y(1010)
      integer*2 NPTS,IOPORT,MODEL,XLEN,YLEN,PPLANE,NUMBR,CTR,NCHAR,
     +          NDIM,ECTR,EDCTR,CNTR,DBFLAG,ELEMNT
      character*1 DISOPT
      character*6 ANS27
      character*25 XTITLE,YTITLE
      character*51 PTITLE
C
C  ...Patience Please !!! ...
         call CLRSCR
         call GOTOXY(12,27)
         write(*,*) 'Calculating Data for Plot'
         call GOTOXY(20,1)
C
      DELTAX=(EMAX-EMIN)/6.
      DELTAY=(EDMAX-EDMIN)/6.
      N=.1
      PI=3.14159
      RA2DEG = N*180./PI
      NDIM=20
      NUMBR=0
C
      if (ELEMNT .eq. 1) then
          ESS=RSLOPE*KV/KP
      elseif ((ELEMNT .eq. 2) .or. (ELEMNT .eq. 3)) then
          ESS=RSLOPE*(F*R+KT*KB+KA*150.*KT*KV*RA2DEG)/
     +     (KT*KP*KA*150.*RA2DEG)
      endif
C
      if (ELEMNT .eq. 1) then
         if (DBAND .eq. 0.) then
            PTITLE='PHASE PLANE CHARACTERISTICS (IDEAL RELAY)'
            PLEN=42.
         elseif (DBAND .ne. 0.) then
            PTITLE='PHASE PLANE CHARACTERISTICS (RELAY WITH DEADBAND)'
            PLEN=50.
         endif
      elseif (ELEMNT .eq. 2) then
         if (DBAND .eq. 0.) then
            PTITLE='PHASE PLANE CHARACTERISTICS (SATURATING AMPLIFIER)'
            PLEN=51.
         elseif (DBAND .ne. 0.) then
            PTITLE='PHASE PLANE CHARACTERISTICS (SAT AMP w/ DEADBAND)'
            PLEN=50.
         endif
      elseif (ELEMNT .eq. 3) then
         if (DBAND .eq. 0.) then
           PTITLE='PHASE PLANE CHARACTERISTICS (PULSE WIDTH MODULATOR)'
            PLEN=51.
         elseif (DBAND .ne. 0.) then
            PTITLE='PHASE PLANE CHARACTERISTICS (PWM w/ DEADBAND)'
            PLEN=46.
         endif
      endif
C
      ASPRAT=.65
      CHARHT=.20
      PTX=1.5+(6.-PLEN*ASPRAT*CHARHT)/2.
      PTY=7.40
      NCHAR=ifix(PLEN)
      CALL PLOTS(0,IOPORT,MODEL)
      call ASPECT(asprat)
      CALL FACTOR(WFACT)
C
      if ((DISOPT .eq. 'M') .or. (DISOPT .eq. 'm')) then
         call PLOT(1.0,0.,-13)
C  ... Draw a Border ...
         call NEWPEN(2)
         call PLOT(0.,0.,3)
         call PLOT(8.,0.,2)
         call PLOT(8.,8.,2)
         call PLOT(0.,8.,2)
         call PLOT(0.,0.,2)
         call NEWPEN(1)
      elseif ((DISOPT .eq. 'P') .or. (DISOPT .eq.'p')) then
         call PLOT(XORG/WFACT,YORG/WFACT,-13)
C ... Draw a border ...
         call PLOT(8.0/WFACT,0.0,2)
         call PLOT(8.0/WFACT,6.0/WFACT,2)
         call PLOT(0.0,6.0/WFACT,2)
         call PLOT(0.0,0.0,2)
         call PLOT(5.55/WFACT,6.0/WFACT,3)
         call PLOT(5.55/WFACT,0.0,2)
C ... Specification Summary
         call SYMBOL(6.55/WFACT,4.0/WFACT,.28,'SUMMARY',0.,7)
         call PLOT(6.55/WFACT,3.95/WFACT,3)
         call PLOT(7.35/WFACT,3.95/WFACT,2)
C
         if (RSLOPE .eq. 0.) then
       call SYMBOL(5.75/WFACT,3.7/WFACT,.22,'Type of Input  STEP',0.,19)
         elseif (RSLOPE .ne. 0.) then
       call SYMBOL(5.75/WFACT,3.7/WFACT,.22,'Type of Input  RAMP',0.,19)
         endif
C
         call SYMBOL(5.75/WFACT,3.4/WFACT,.22,'Start Time     ',0.,15)
```

```
           call NUMBER(999.,3.4/WFACT,.22,BEGTIM,0.,5)
           call SYMBOL(5.75/WFACT,3.1/WFACT,.22,'Stop Time       ',0.,15)
           call NUMBER(999.,3.1/WFACT,.22,FINTIM,0.,5)
           call SYMBOL(5.75/WFACT,2.8/WFACT,.22,'KP              ',0.,15)
           call NUMBER(999.,2.8/WFACT,.22,KP,0.,5)
           call SYMBOL(5.75/WFACT,2.5/WFACT,.22,'KV              ',0.,15)
           call NUMBER(999.,2.5/WFACT,.22,KV,0.,5)
           call SYMBOL(5.75/WFACT,2.2/WFACT,.22,'Ess             ',0.,15)
           call NUMBER(999.,2.2/WFACT,.22,ESS+DBAND,0.,5)
           if ((ELEMNT .eq. 2) .or. (ELEMNT .eq. 3)) then
          call SYMBOL(5.75/WFACT,1.9/WFACT,.22,'GAIN            ',0.,15)
          call NUMBER(999.,1.9/WFACT,.22,KA,0.,5)
           endif
           if (ELEMNT .eq. 3) then
          call SYMBOL(5.75/WFACT,1.6/WFACT,.22,'PWM Freq (Hz)   ',0.,15)
          call NUMBER(999.,1.6/WFACT,.22,1./PERIOD,0.,1)
           endif
C
      endif
C  ... Draw a Title
      call SYMBOL(PTX,PTY,CHARHT,PTITLE,0.,NCHAR)
C
C ... Redefine origin ...
      call PLOT(1.,1.0,-13)
C
      CALL STAXIS(.18,CHARHT,.10,.080,2)
      CALL AXIS(0.0,0.0,'E',-1,6.,0.,EMIN,DELTAX)
C
      CALL STAXIS(.18,CHARHT,.10,.080,1)
      CALL AXIS(0.,0.,'E DOT',5,6.,90.,EDMIN,DELTAY)
C
C  ... Generation of Limit Lines (Discontinuity)
       if (KV .eq. 0.) then
C  ... Positive Deadband & Relay Switching ...
           L1X1=DBAND+ESS
           L1X2=DBAND+ESS
           L1Y1=EDMIN+(EDMAX-EDMIN)/float(NDIM)
           L1Y2=EDMAX
C
C  ... Negative Deadband ...
           L2X1=-DBAND+ESS
           L2X2=-DBAND+ESS
           L2Y1=EDMIN+(EDMAX-EDMIN)/float(NDIM)
           L2Y2=EDMAX
C
      if (KA .ne. 0.) then
C  ... Positive Saturation ...
           L3X1=1./KA+DBAND+ESS
           L3X2=1./KA+DBAND+ESS
           L3Y1=EDMIN+(EDMAX-EDMIN)/float(NDIM)
           L3Y2=EDMAX
```

```
C
C  ... Negative Saturation ...
           L4X1=-(1./KA+DBAND)+ESS
           L4X2=-(1./KA+DBAND)+ESS
           L4Y1=EDMIN+(EDMAX-EDMIN)/float(NDIM)
           L4Y2=EDMAX
     endif
C
      elseif (KV .ne. 0.) then
C     ... Point (X1,Y1) of Line 1 ...
           if ((DBAND-EMIN+ESS)*KP/KV .le. EDMAX) then
              L1X1=EMIN+(EMAX-EMIN)/float(NDIM)
              L1Y1=(DBAND-(EMIN+(EMAX-EMIN)/float(NDIM))+ESS)*KP/KV
           elseif ((DBAND-EMIN+ESS)*KP/KV .gt. EDMAX) then
              L1X1=DBAND-EDMAX*KV/KP+ESS
              L1Y1=EDMAX
           endif
C     ... Point (X2,Y2) of Line 1 ...
           if ((DBAND-EMAX+ESS)*KP/KV .ge. EDMIN) then
              L1X2=EMAX
              L1Y2=(DBAND-EMAX+ESS)*KP/KV
           elseif ((DBAND-EMAX+ESS)*KP/KV .lt. EDMIN) then
             L1X2=DBAND-((EDMIN+(EDMAX-EDMIN)/float(NDIM)))*KV/KP+ESS
              L1Y2=EDMIN+(EDMAX-EDMIN)/float(NDIM)
           endif
C     ... Point (X1,Y1) of Line 2 ...
           if ((-DBAND-EMIN+ESS)*KP/KV .le. EDMAX) then
              L2X1=EMIN+(EMAX-EMIN)/float(NDIM)
              L2Y1=(-DBAND-(EMIN+(EMAX-EMIN)/float(NDIM))+ESS)*KP/KV
           elseif ((-DBAND-EMIN+ESS)*KP/KV .gt. EDMAX) then
              L2X1=-DBAND-EDMAX*KV/KP+ESS
              L2Y1=EDMAX
           endif
C     ... Point (X2,Y2) of Line 2 ...
           if ((-DBAND-EMAX+ESS)*KP/KV .ge. EDMIN) then
              L2X2=EMAX
              L2Y2=(-DBAND-EMAX+ESS)*KP/KV
           elseif ((-DBAND-EMAX+ESS)*KP/KV .lt. EDMIN) then
              L2X2=-DBAND-(EDMIN+(EDMAX-EDMIN)/float(NDIM))*KV/KP+ESS
              L2Y2=EDMIN+(EDMAX-EDMIN)/float(NDIM)
           endif
           if (KA .ne. 0.) then
C     ... Point (X1,Y1) of Line 3 ...
           if ((1./KA+DBAND-EMIN+ESS)*KP/KV .le. EDMAX) then
              L3X1=EMIN+(EMAX-EMIN)/float(NDIM)
         L3Y1=(1./KA+DBAND-(EMIN+(EMAX-EMIN)/float(NDIM))+ESS)*KP/KV
           elseif ((1./KA+DBAND-EMIN+ESS)*KP/KV .gt. EDMAX) then
              L3X1=1./KA+DBAND-EDMAX*KV/KP+ESS
              L3Y1=EDMAX
           endif
C     ... Point (X2,Y2) of Line 3 ...
```

```
              if ((1./KA+DBAND-EMAX+ESS)*KP/KV .ge. EDMIN) then
                 L3X2=EMAX
                 L3Y2=(1./KA+DBAND-EMAX+ESS)*KP/KV
              elseif ((1./KA+DBAND-EMAX+ESS)*KP/KV .lt. EDMIN) then
            L3X2=1./KA+DBAND-(EDMIN+(EDMAX-EDMIN)/float(NDIM))*KV/KP+ESS
                 L3Y2=EDMIN+(EDMAX-EDMIN)/float(NDIM)
              endif
C        ... Point (X1,Y1) of Line 4 ...
              if ((-1./KA-DBAND-EMIN+ESS)*KP/KV .le. EDMAX) then
                 L4X1=EMIN+(EMAX-EMIN)/float(NDIM)
             L4Y1=(-1./KA-DBAND-(EMIN+(EMAX-EMIN)/float(NDIM))+ESS)*KP/KV
              elseif ((-1./KA-DBAND-EMIN+ESS)*KP/KV .gt. EDMAX) then
                 L4X1=-1./KA-DBAND-EDMAX*KV/KP+ESS
                 L4Y1=EDMAX
              endif
C        ... Point (X2,Y2) of Line 4 ...
              if ((-1./KA-DBAND-EMAX+ESS)*KP/KV .ge. EDMIN) then
                 L4X2=EMAX
                 L4Y2=(-1./KA-DBAND-EMAX+ESS)*KP/KV
              elseif ((-1./KA-DBAND-EMAX+ESS)*KP/KV .lt. EDMIN) then
           L4X2=-1./KA-DBAND-(EDMIN+(EDMAX-EDMIN)/float(NDIM))*KV/KP+ESS
                 L4Y2=EDMIN+(EDMAX-EDMIN)/float(NDIM)
              endif
              endif
         endif
C
C    ... Points are Scaled to Real World Values ..
C    ... Line #1
           L1X1S=(L1X1-EMIN)/DELTAX
           L1Y1S=(L1Y1-EDMIN)/DELTAY
           L1X2S=(L1X2-EMIN)/DELTAX
           L1Y2S=(L1Y2-EDMIN)/DELTAY
C    ... Line #2
           L2X1S=(L2X1-EMIN)/DELTAX
           L2Y1S=(L2Y1-EDMIN)/DELTAY
           L2X2S=(L2X2-EMIN)/DELTAX
           L2Y2S=(L2Y2-EDMIN)/DELTAY
C    ... Line #3
           L3X1S=(L3X1-EMIN)/DELTAX
           L3Y1S=(L3Y1-EDMIN)/DELTAY
           L3X2S=(L3X2-EMIN)/DELTAX
           L3Y2S=(L3Y2-EDMIN)/DELTAY
C    ... Line #4
           L4X1S=(L4X1-EMIN)/DELTAX
           L4Y1S=(L4Y1-EDMIN)/DELTAY
           L4X2S=(L4X2-EMIN)/DELTAX
           L4Y2S=(L4Y2-EDMIN)/DELTAY
C
           if (ELEMNT .eq. 3) then
              ELEMNT=2
              FLAG=1.
```

```
          endif
C
C  ... Plotting of Dashed Limit Lines ...
          call STDASH(.05,.15)
          call PLOTD(L1X1S,L1Y1S,3)
          call PLOTD(L1X2S,L1Y2S,2)
          if (DBAND .ne. 0.) then
            call PLOTD(L2X1S,L2Y1S,3)
            call PLOTD(L2X2S,L2Y2S,2)
          endif
          if ((ELEMNT .eq. 2) .and. (KA .ne. 0.)) then
            call PLOTD(L3X1S,L3Y1S,3)
            call PLOTD(L3X2S,L3Y2S,2)
            call PLOTD(L4X1S,L4Y1S,3)
            call PLOTD(L4X2S,L4Y2S,2)
          endif
C
C  ... Phase Plane Slope Marker Generation and Plotting ...
        do 415 ECTR=1,NDIM
          E=EMIN+((EMAX-EMIN)/FLOAT(NDIM))*FLOAT(ECTR)
          do 425 EDCTR=1,NDIM
             DBFLAG=0
             NUMBR=NUMBR+1
             EDOT=EDMIN+((EDMAX-EDMIN)/FLOAT(NDIM))*FLOAT(EDCTR)
          if (abs(E+EDOT*KV/KP-ESS) .le. DBAND) then
C  ... Deadband Region ...
                if (EDOT .ne. 0.) then
                  SLOPEX=J*R*EDOT/DELTAX
                  SLOPEY=-(KT*KB+F*R)*(EDOT-RSLOPE)/DELTAY
                elseif (EDOT .eq. 0.) then
                  DBFLAG=1
                  SLOPEX=0.
                  SLOPEY=1.
                endif
C  ... Positive Saturation Region ...
          elseif (((ELEMNT .eq. 1) .and. (E+EDOT*KV/KP-ESS .gt.
     +      DBAND)) .or. ((ELEMNT.eq.2) .and. (((E+EDOT*KV/KP-ESS)
     +      -DBAND)*KA .ge. 1.))) then
                  SLOPEX=J*R*(EDOT)/DELTAX
                  SLOPEY=-(150.*KT*KP*RA2DEG+(KT*KB+F*R)*(EDOT-RSLOPE))/
     +                   DELTAY
C  ... Negative Saturation Region ...
          elseif (((ELEMNT .eq. 1) .and. (E+EDOT*KV/KP-ESS .lt.
     +      -DBAND)) .or. ((ELEMNT.eq.2) .and. (((E+EDOT*KV/KP-ESS)
     +      +DBAND)*KA .le. -1.))) then
                  SLOPEX=J*R*(EDOT)/DELTAX
                  SLOPEY=-(-150.*KT*KP*RA2DEG+(KT*KB+F*R)*(EDOT-RSLOPE))/
     +                   DELTAY
C  ... Positive LINEAR Region ...
          elseif ((((E+(EDOT)*KV/KP)-ESS-DBAND)*KA .gt. 0.) .and.
     +            (((E+(EDOT)*KV/KP)-ESS-DBAND)*KA .lt. 1.)) then
```

```
                 SLOPEX=J*R*(EDOT)/DELTAX
                 V=150.*((E+(EDOT-RSLOPE)*KV/KP)-DBAND)*KA
                 SLOPEY=-(V*KT*KP*RA2DEG+(KT*KB+F*R)*(EDOT-RSLOPE))/
     +                  DELTAY
C  ... Negative LINEAR Region ...
         elseif ((((E+(EDOT)*KV/KP-ESS)+DBAND)*KA .lt. 0.) .and.
     +           (((E+(EDOT)*KV/KP-ESS)+DBAND)*KA .gt. -1.)) then
                 SLOPEX=J*R*(EDOT)/DELTAX
                 V=150.*((E+(EDOT-RSLOPE)*KV/KP)+DBAND)*KA
                 SLOPEY=-(V*KT*KP*RA2DEG+(KT*KB+F*R)*(EDOT-RSLOPE))/
     +                   DELTAY
         endif
C
C  ... Points are Scaled to Real World Coordinates ...
              VECLEN=sqrt(SLOPEX**2+SLOPEY**2)
              E1X=(E-EMIN)/DELTAX
              E2X=E1X+.15*SLOPEX/VECLEN
              E1Y=(EDOT-EDMIN)/DELTAY
              E2Y=E1Y+.15*SLOPEY/VECLEN
C
C  ... Filter out end point for ideal relay ...
              if ((E .ne. ESS) .or. (EDOT .ne. 0.)) then
C  ... Filter out end points for relay with Dead Band ...
                 if (DBFLAG .eq. 0) then
                    call PLOT(E1X,E1Y,3)
                    call PLOT(E2X,E2Y,2)
                 endif
              endif
              call SYMBOL(E1X,E1Y,.04,1,0.,-1)
C
  425    continue
  415 continue
C
       if ((ANS27 .ne. 'n') .and. (ANS27 .ne. 'N')) then
C  ... Overlay a Phase Plane Trajectory ...
         X(NPTS+1)=EMIN
         X(NPTS+2)=DELTAX
         Y(NPTS+1)=EDMIN
         Y(NPTS+2)=DELTAY
         call LINE(X,Y,NPTS,1,0,0)
C
C  ... Mark the Start of the Trajectory (Real World Coordinates)...
         XMARK1= (X(1)-EMIN)/DELTAX
         YMARK1= (Y(1)-EDMIN)/DELTAY
         call SYMBOL(XMARK1,YMARK1,.12,0,0.,-1)
C
C  ... Mark the Ordered Position (Real World Coordinates)...
         XMARK2= (ESS+DBAND-EMIN)/DELTAX
         YMARK2= (0.-EDMIN)/DELTAY
         call SYMBOL(XMARK2,YMARK2,.14,11,0.,-1)
       endif
```

```
C
      CALL PLOT(0.0,0.0,999)
C
      if (FLAG .eq. 1.) then
         ELEMNT=3
         FLAG=0.
      endif
C
C
      RETURN
      END
C  *********************************
C  ***** PLOTTING SUBROUTINES *****
C  *****(multi- function plot)*****
C  *****  (Printer Function)  *****
C  *********************************
      Subroutine MGRAPH(DISOPT,KAPWM,DBAND,X0,Y0,WFACT1,ELEMNT)
C
      implicit REAL*4 (A-Z)
      COMMON XTIME,Y1,Y2,Y3,Y4,BEGTIM,FINTIM,NPTS,IOPORT,MODEL,
     +    XLEN,YLEN,PLEN,PPLANE,XTITLE,YTITLE,PTITLE
      real*4 XTIME(1010),Y1(1010),Y2(1010),Y3(1010),Y4(1010)
      integer*2 NPTS,IOPORT,MODEL,XLEN,YLEN,PPLANE,ELEMNT
      character*1 DISOPT
      character*3 ANS
      character*20 XTITLE,YTITLE
      character*51 PTITLE
C
        WFACT=(2./3.)*WFACT1
C  ...Time axis ...
        XTIME(NPTS+1)=BEGTIM
        FIRSTX = BEGTIM
        XTIME(NPTS+2)=(BEGTIM-FINTIM)/10.
        DELTAX = (FINTIM-BEGTIM)/10.
C
        call SCALE(Y1,4.,NPTS,1)
        MINY1=Y1(NPTS+1)
        DELY1=Y1(NPTS+2)
      if (ELEMNT .ne. 3) then
         call SCALE(Y3,5.,NPTS,1)
         MINY3=Y3(NPTS+1)
         DELY3=Y3(NPTS+2)
         Y2(NPTS+1)=MINY3
         Y2(NPTS+2)=DELY3
         MINY2=MINY3
         DELY2=DELY3
      else
         Y3(NPTS+1)=-1.0
         Y3(NPTS+2)=.2
         MINY3=0.
         DELY3=.2
         Y2(NPTS+1)=-1.0
         Y2(NPTS+2)=.2
         MINY2=0.
         DELY2=.2
      endif
        Y4(NPTS+1)=-12.
        Y4(NPTS+2)=1.
      CALL PLOTS(0,IOPORT,MODEL)
      CALL FACTOR(WFACT)
      if ((DISOPT .eq. 'M') .or. (DISOPT .eq. 'm')) then
         call PLOT(2.5,1.,-13)
      elseif ((DISOPT .eq. 'P') .or. (DISOPT .eq. 'p')) then
         call PLOT(X0/WFACT,Y0/WFACT,-13)
C ... Draw a border ...
         call PLOT(16.0,0.0,2)
         call PLOT(16.0,12.0,2)
         call PLOT(0.0,12.0,2)
         call PLOT(0.0,0.0,2)
C ... Redefine origin ...
         call PLOT(1.3,11.0,-13)
      endif
C
      CALL STAXIS(.20,.27,.16,.080,2)
      CALL AXIS(0.0,0.0,'TIME (sec)',-10,10.,270.,FIRSTX,DELTAX)
C
      CALL STAXIS(.20,.27,.16,.080,1)
      CALL AXIS(0.,0.,'ERROR SIGNAL',12,4.,0.,MINY1,DELY1)
      CALL LINE(Y1,XTIME,NPTS,1,0,0)
C
      CALL AXIS(5.,0.,'REFERENCE SIGNAL',16,5.,0.,MINY2,DELY2)
      CALL LINE(Y2,XTIME,NPTS,1,0,0)
C
      CALL AXIS(5.,-10.,'THRESHOLD VOLTAGE',-17,5.,0.,MINY3,DELY3)
      CALL NEWPEN(2)
      CALL LINE(Y3,XTIME,NPTS,1,0,0)
      CALL NEWPEN(1)
C
      CALL STAXIS(.20,.27,.13,.080,-1)
      CALL AXIS(11.,0.,'DIRECTIONAL LOGIC',17,2.,0.,-1.,1.)
      CALL LINE(Y4,XTIME,NPTS,1,0,0)
C
      PTITLE='CLOSED LOOP PERFORMANCE'
      call SYMBOL(14.2,-.5,.38,PTITLE,270.,23)
      if (ELEMNT .eq. 1) call SYMBOL(14.2,999.,.38,' (AMP)',270.,6)
      if (ELEMNT .eq. 2) call SYMBOL(14.2,999.,.38,' (RELAY)',270.,8)
      if (ELEMNT .eq. 3) call SYMBOL(14.2,999.,.38,' (PWM)',270.,6)
      call SYMBOL(13.6,-1.0,.3,'GAIN = ',270.,7)
      if (ELEMNT .ne. '2') then
        call NUMBER(13.6,999.,.3,KAPWM,270.,2)
      elseif (ELEMNT .eq. '2') then
        call SYMBOL(13.6,999.,.3,236,270.,+1)
      endif
      call SYMBOL(13.6,-5.0,.3,'DEAD ZONE = ',270.,12)
      call NUMBER(13.6,999.,.3,DBAND,270.,2)
C
      CALL PLOT(0.0,0.0,999)
C
      MODEL=99
      IOPORT=99
C
      RETURN
      END
C ********************************
C ***** PLOTTING SUBROUTINES *****
C *****(multi- function plot)*****
C *****  (Monitor Function)  *****
C ********************************
      Subroutine M1GRAPH(ELEMNT)
C
      implicit REAL*4 (A-Z)
      COMMON XTIME,Y1,Y2,Y3,Y4,BEGTIM,FINTIM,NPTS,IOPORT,MODEL,
     +    XLEN,YLEN,PLEN,PPLANE,XTITLE,YTITLE,PTITLE
      real*4 XTIME(1010),Y1(1010),Y2(1010),Y3(1010),Y4(1010)
      integer*2 NPTS,IOPORT,MODEL,XLEN,YLEN,PPLANE,ELEMNT
      character*25 XTITLE,YTITLE
      character*51 PTITLE
C
C ...Patience Please !!! ...
         call CLRSCR
         call GOTOXY(12,27)
         write(*,*) 'Calculating Data for Plot'
         call GOTOXY(20,1)
C
        WFACT=.55
C ...Time axis ...
      CALL SCALE(XTIME,10.,NPTS,1)
        FIRSTX = XTIME(NPTS+1)
        XTIME(NPTS+2)=(XTIME(NPTS)-XTIME(NPTS+1))/10.
        DELTAX = XTIME(NPTS+2)
C
        Y4(NPTS+1)=-8.
        Y4(NPTS+2)=1.
      CALL PLOTS(0,IOPORT,MODEL)
      CALL FACTOR(WFACT)
      CALL PLOT(2.5,1.,-13)
C
      CALL STAXIS(.18,.25,.10,.080,3)
      CALL AXIS(0.0,0.0,XTITLE,XLEN,10.,0.,FIRSTX,DELTAX)
C
      if (ELEMNT .ne. 3) then
         call SCALE(Y3,5.,NPTS,1)
         MINY3=Y3(NPTS+1)
         DELY3=Y3(NPTS+2)
      else
         Y3(NPTS+1)=0.
         Y3(NPTS+2)=.2
         MINY3=0.
         DELY3=.2
      endif
      CALL AXIS(10.,0.,'ERROR VOLTAGE',-13,5.,90.,MINY3,DELY3)
      CALL LINE(XTIME,Y3,NPTS,1,0,0)
C
      Y2(NPTS+1)=MINY3
      Y2(NPTS+2)=DELY3
      CALL STAXIS(.18,.25,.10,.080,2)
      CALL AXIS(0.,0.,'REFERENCE SIGNAL',16,5.,90.,MINY3,DELY3)
      CALL LINE(XTIME,Y2,NPTS,1,0,0)
C
      CALL STAXIS(.18,.25,.10,.080,-1)
      CALL AXIS(0.,7.,YTITLE,YLEN,2.,90.,-1.,1.)
      CALL LINE(XTIME,Y4,NPTS,1,0,0)
C
      CALL PLOT(0.0,0.0,999)
C
      MODEL=99
      IOPORT=99
C
      RETURN
      END
C
C     ******************************************
C     ***** PULSE WIDTH MODULATOR MODULE *****
C     ******************************************
C
      Subroutine PWMOD(TIME,NUMIT,TSTART,PERIOD,TOGGLE,POSERR,
     +    DBAND,AGCSAT,AGCCUT,ERRSAT,ERRCUT,VIN,VREF,THRESH,KPWM)
C
      IMPLICIT REAL*4 (A-Z)
      INTEGER*2 NUMIT,DIR
      LOGICAL*2 WAITNG,TOGGLE
C
C ... Reset the saw-tooth reference signal ...
        if (TIME .ge. TSTART+PERIOD) then
          TSTART=TSTART+PERIOD
          TOGGLE=.true.
        endif
C
        if (POSERR .gt. (0.+DBAND)) then
          DIR=1
          ERROR=abs(KPWM*(POSERR-DBAND))
        elseif (POSERR .lt. (0.-DBAND)) then
          DIR=-1
          ERROR=abs(KPWM*(POSERR+DBAND))
        else
          ERROR=0.
        endif
        call LIMIT(0.,1.,ERROR,ERROR)
        call RAMP(TIME,TSTART,NREF)
        VREF=NREF/PERIOD
        THRESH=1.-ERROR
C
C ... "WAITING" is a logical variable indicating whether or not a new
C       pulse may be generated ...
        if (NUMIT .eq. 1) WAITNG=TOGGLE
C
        if (WAITNG) then
          if (VREF .gt. THRESH) then
            if (DIR .eq. 1) then
              VIN=150.
              TOGGLE=.false.
            elseif (DIR .eq. -1) then
              VIN=-150.
              TOGGLE=.false.
            endif
          elseif (VREF .lt. THRESH) then
            VIN=0.
            TOGGLE=.true.
          endif
        endif
C
      return
      end
C
C    *************************
C    ***** RELAY MODULE *****
C    *************************
C
      Subroutine RELAY(POSERR,DBAND,VIN)
C
      implicit REAL*4 (A-Z)
C
         if (POSERR .gt. DBAND) then
            VIN=150.
         elseif (POSERR .lt. -DBAND) then
            VIN=-150.
         elseif (abs(POSERR) .le. DBAND) then
            VIN=0.
         endif
C
      return
      end
C
C    ****************************************
C    ***** SATURATING AMPLIFIER MODULE *****
```

```
C     ******************************************
C
       Subroutine AMPLIF(POSERR,DBAND,KA,VIN)
C
       implicit REAL*4 (A-Z)
C
          if (abs(POSERR) .le. DBAND) then
             VIN=0.
          elseif (((POSERR-DBAND)*KA .gt. 0.) .and.
     +             ((POSERR-DBAND)*KA .lt. 1.)) then
             VIN=150.*(POSERR-DBAND)*KA
          elseif (((POSERR+DBAND)*KA .lt. 0.) .and.
     +             ((POSERR+DBAND)*KA .gt. -1.)) then
             VIN=150.*(POSERR+DBAND)*KA
          elseif ((POSERR-DBAND)*KA .ge. 1.) then
             VIN=150.
          elseif ((POSERR+DBAND)*KA .le. -1.) then
             VIN=-150.
          endif
C
       return
       end
C
C     *****************************************************
C     ***** Cutoff-Saturation Limiting Subroutine *****
C     *****************************************************
           Subroutine LIMIT(RSAT,RCUT,INPUT,OUT)
             implicit REAL*4 (A-Z)
             if (INPUT .le. RSAT) then
               OUT=RSAT
             elseif (INPUT .ge. RCUT) then
               OUT=RCUT
             else
               OUT=INPUT
             end if
C
           return
           end
C     ****************************************
C     ***** Function Switch Subroutine *****
C     ****************************************
         Subroutine FCNSW(X1,X2,X3,X4,OUT)
           implicit REAL*4 (A-Z)
           if (X1 .lt. 0.0) then
             OUT=X2
           elseif (X1 .eq. 0.0) then
             OUT=X3
           else
             OUT=X4
           end if
C
```

```
      return
      end
C    ***************************************
C    ***** Step function Subroutine *****
C    ***************************************
      Subroutine STEP(TIME,TSTEP,OUT)
        implicit REAL*4 (A-Z)
        if (TIME .ge. TSTEP) then
          OUT=1.0
        else
          OUT=0.0
        end if
C
      return
      end
C    **********************************
C    ***** Deadspace Subroutine *****
C    **********************************
      Subroutine DEADSP(P1,P2,VSGDEL,VSGERR)
        implicit REAL*4 (A-Z)
        if (VSGDEL .gt. P2) then
          VSGERR=VSGDEL-P2
        elseif (VSGDEL .lt. P1) then
          VSGERR=VSGDEL-P1
        else
          VSGERR=0.0
        end if
C
      return
      end
C    ****************************
C    ***** Ramp Subroutine *****
C    ****************************
      Subroutine RAMP(TIME,TRAMP,OUT)
        implicit REAL*4 (A-Z)
        if (TIME .ge. TRAMP) then
          OUT=TIME-TRAMP
        else
          OUT=0.0
        end if
C
      return
      end
C     **********************
C     *** TIME CONSTANT ***
C     **********************
C
     Subroutine TCONST(Y0,X,TAU,NTIME,NTIM,DELTIM,Y)
      implicit real*4 (A-Z)
      integer*2 NTIME,NTIM
      if (NTIME .ne. NTIM) Y0=Y
```

```
         DECAY=exp(-DELTIM/TAU)
         Y=Y0+(X-Y0)*(1.-DECAY)
         if (NTIME .eq. 1) Y=Y0
         NTIM=NTIME
C
        return
        end
C     ************************************************
C     ***** First Order Derivative Subroutine *****
C     ************************************************
         Subroutine DERIV(DELTIM,NTIME,NTIM1,IC2,XM1,NOWVAL,XX,XDM1,
     +                    XD,XDDM1,XDD,SLOPE)
           implicit REAL*4 (A-Z)
           integer*2 NTIME,NTIM1
C
           if (NTIME .eq. NTIM1) then
             XX=NOWVAL
           else
             XM1=XX
             XX=NOWVAL
             XDM1=XD
             XDDM1=XDD
           end if
C
           XD=(XX-XM1)/DELTIM
           if (abs(XD) .lt. 1.E-8) XD=0.
           if (NTIME .eq. 1) XD=IC2
           XDD=(XD-XDM1)/DELTIM
           if (abs(XDD) .lt. 1.E-8) XDD=0.0
C
           NTIM1=NTIME
C
           XPRED=XX+XD*DELTIM+XDD*(DELTIM**2)/2.0
           if (abs(XPRED) .lt. 1.E-8) XPRED=0.0
           SLOPE=(XPRED-XM1)/(2.0*DELTIM)
           if (abs(SLOPE) .lt. 1.E-8) SLOPE=0.0
C
         return
         end
C     **************************************************
C     ***** Trapezoidal Integration Subroutine *****
C     **************************************************
         Subroutine INTGRL(NTIME,NTIM2,DELTIM,IC3,PREVAL,NOWVAL,
     +                    CURVAL,OUTOLD,OUTNEW)
           implicit REAL*4 (A-Z)
           integer*2 NTIME,NTIM2
C
           if (NTIME .eq. NTIM2) then
             CURVAL=NOWVAL
           else
             PREVAL = CURVAL
```

```
            CURVAL = NOWVAL
            OUTOLD = OUTNEW
          end if
          if (NTIME .eq. 1) OUTOLD=IC3
          OUTNEW  = OUTOLD+(CURVAL+PREVAL)*DELTIM/2.
          NTIM2=NTIME
C
        return
        end
C    *******************************************
C    ***** CLEAR SCREEN AND HOME CURSOR *****
C    *******************************************
      subroutine CLRSCR
      character*1 C1,C2,C3,C4
      integer*2 IC(4)
      equivalence (C1,IC(1)),(C2,IC(2)),(C3,IC(3)),(C4,IC(4))
      data IC/16#1B,16#5B,16#32,16#4A/
C
C *** Write Escape Code to Display ***
      write(*,1) C1,C2,C3,C4
    1 format(1X,4A1)
C
      return
      end
C    *******************************************
C    ***** Position Cursor by Row,Column *****
C    *******************************************
      subroutine GOTOXY(ROW,COLUMN)
      integer*2 IC(4),ROW,COLUMN,L
      character*1 C1,C2,C5,C8,LC(5)
      character*5 CBUFF
      equivalence (C1,IC(1)),(C2,IC(2)),(C5,IC(3)),(C8,IC(4)),
     +            (CBUFF,LC(1))
      data IC/16#1B,16#5B,16#3B,16#66/
C
      L=10000+100*ROW+COLUMN
C
C *** Write Escape Codes to a Character Buffer ***
      write(CBUFF,2) L
    2 format(I5)
C
C *** Write Escape Codes to Display ***
      write(*,3) C1,C2,LC(2),LC(3),C5,LC(4),LC(5),C8
    3 format(1X,8A1,\)
      return
      end
```

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